

# Development of a High-Speed Detection Method for Alpha Particle Tracks in Nuclear Emulsion Using Machine Learning

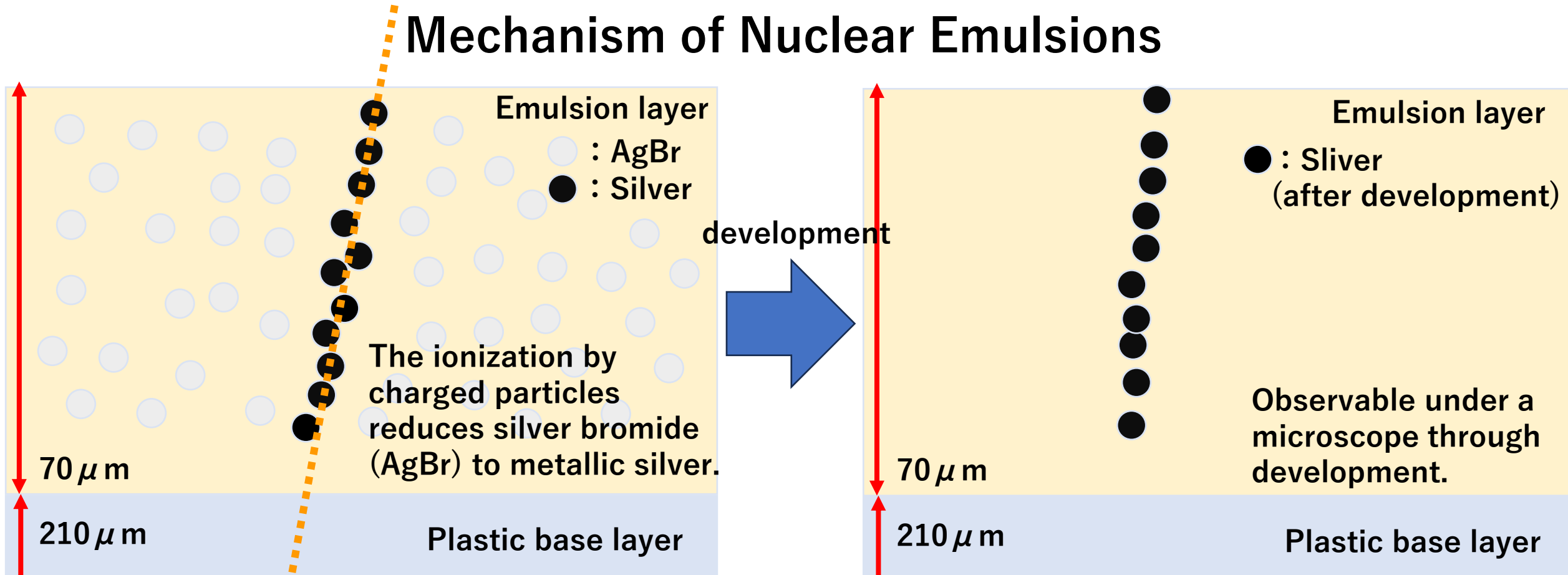
**Tsukasa Nishikiori<sup>1</sup>**

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# Nuclear emulsions

- Nuclear emulsions are a type of track detector that can record the trajectories of charged particles passing through them with micrometer-level precision, and thus have been used in particle physics experiments.



# The history of Nagoya and nuclear emulsions <sup>3</sup>

1971

by Human

Automatic

2000

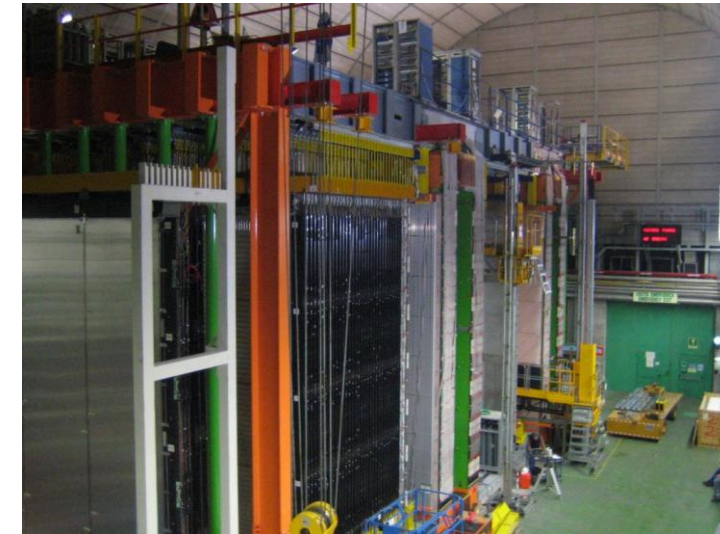
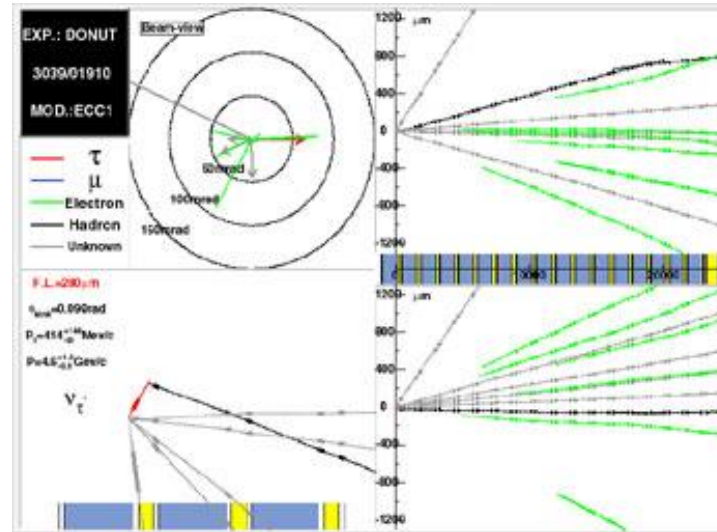
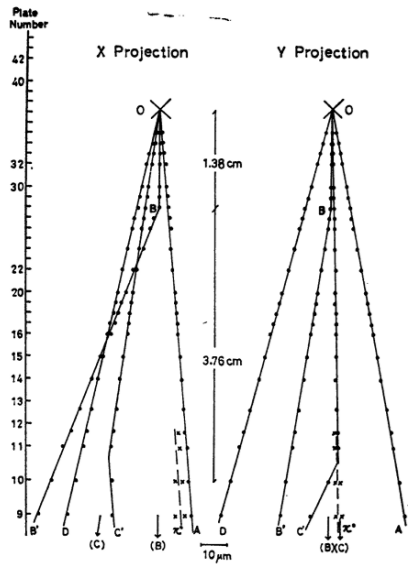
2015

Discovery of the charm particle (Prof.Niu)

Development of an automatic track-reading system

First direct detection of the  $\nu_\tau$  (DoNuT)

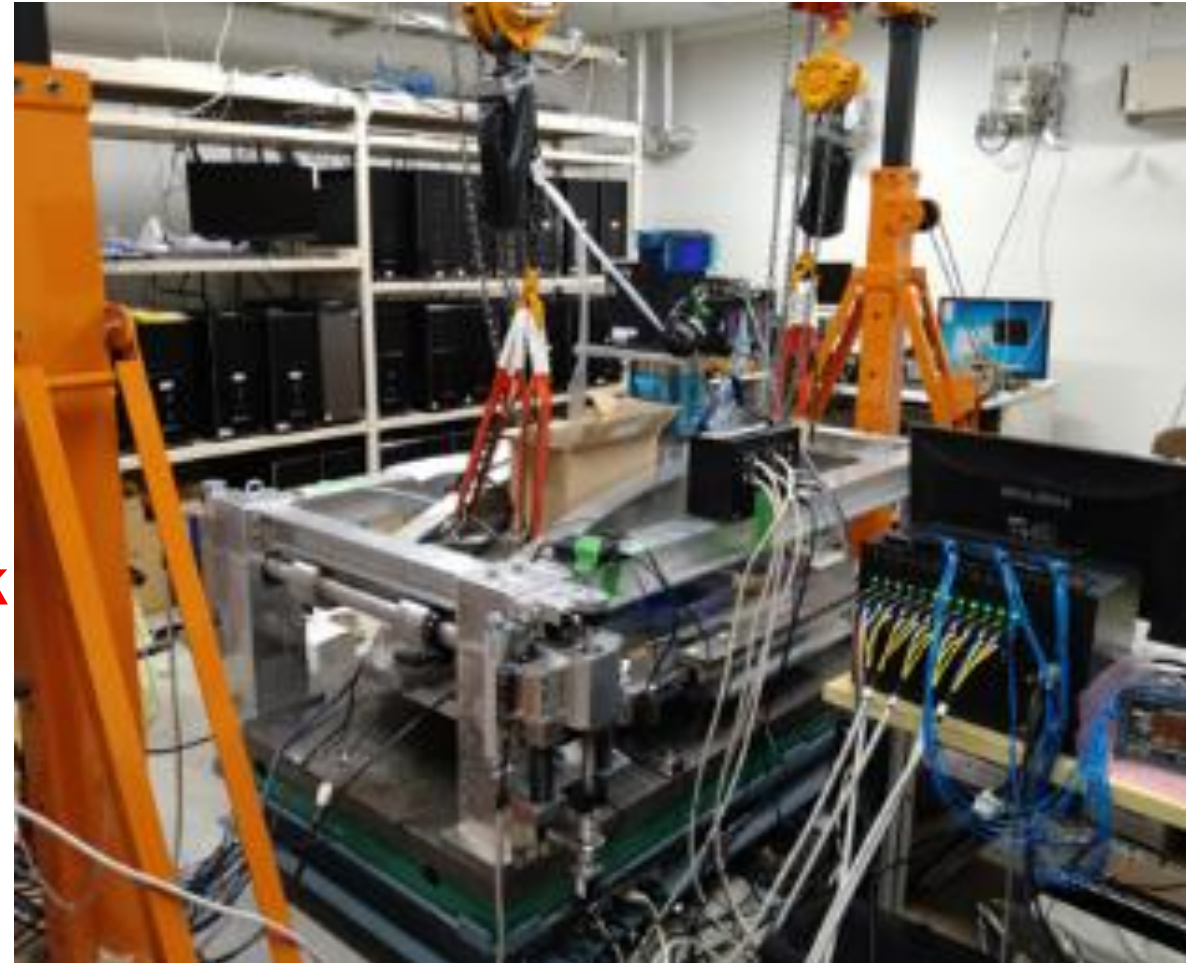
Appearance of  $\nu_\tau$  from neutrino oscillation(OPERA)



- Nagoya has a long history of conducting automatic analysis of nuclear emulsions!

- **Track Selector (TS):** A device that reads particle tracks recorded in nuclear emulsions at ultra-high speed
- Developed in 1985, and through continuous improvements, the current active system is the **HTS2 (Hyper Track Selector)**

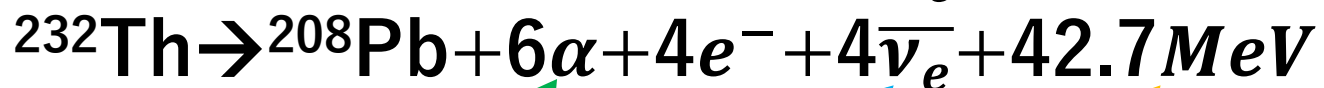
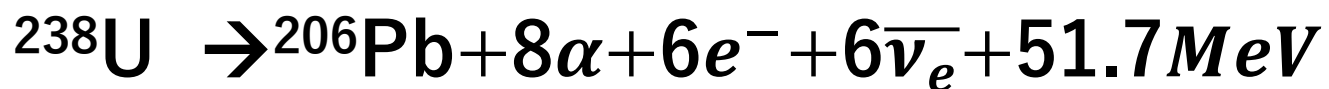
HTS 2



# Challenges in geoneutrino observation

5

- U and Th emit  $\bar{\nu}_e$  during their decay.



$\alpha$  particle

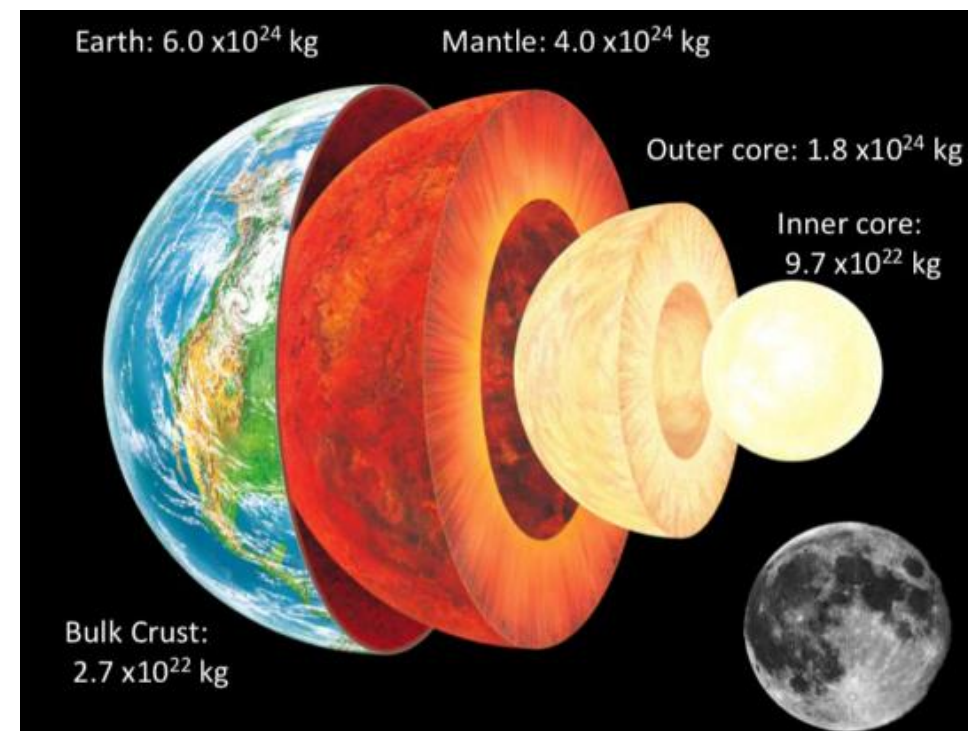
Neutrino

Heat of Earth

→ Observing  $\bar{\nu}_e$  from inside the Earth reveals the geothermal distribution.

→ Uncertainties in crustal neutrino flux models currently limit information on mantle neutrinos.

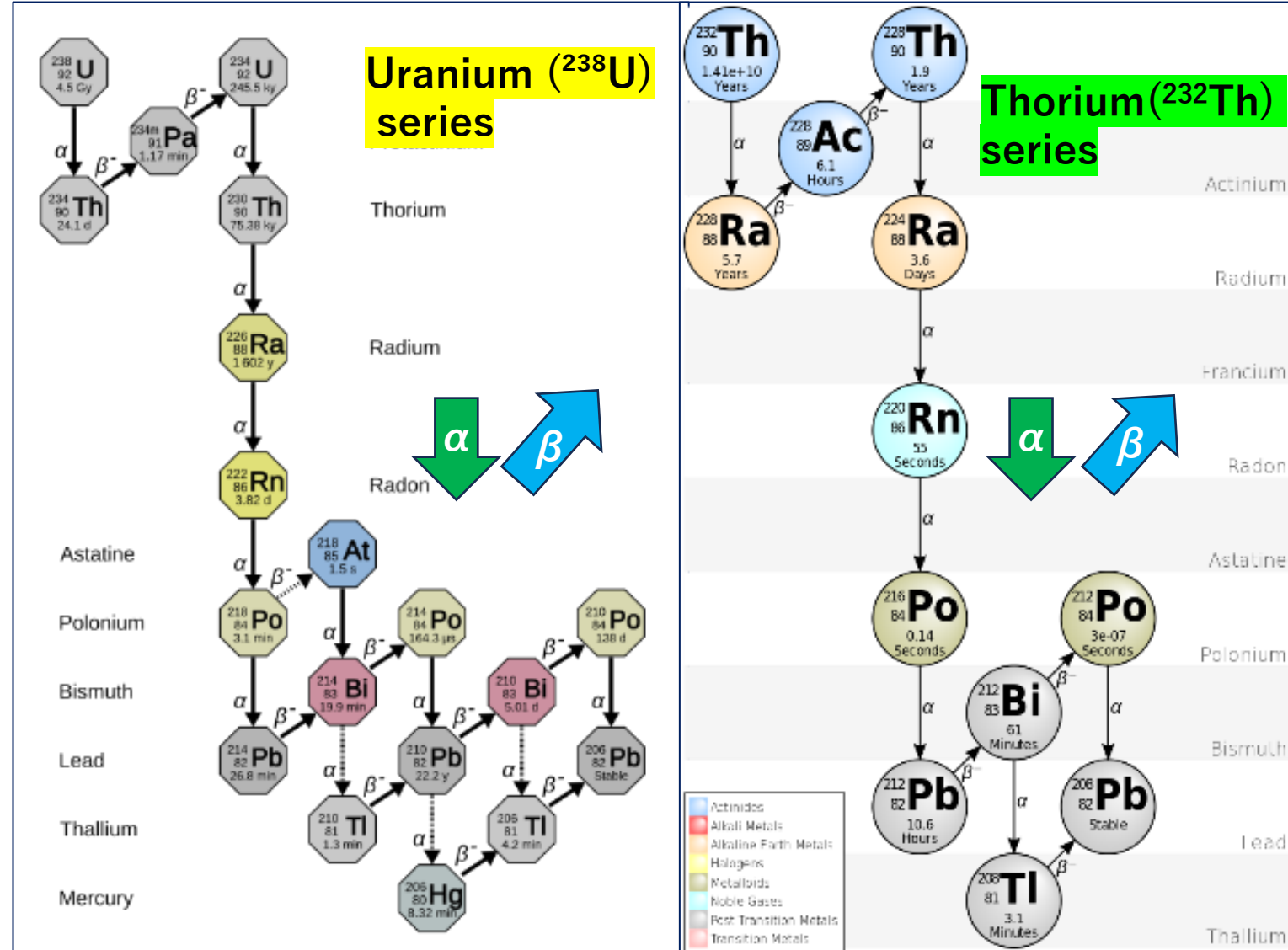
→ Investigating large-area  $\alpha$  decays of U and Th, which are sources of  $\bar{\nu}_e$ .



Expected sources of geoneutrinos: The flux of  $\bar{\nu}_e$  strongly depends on nearby continental crust, making its detailed analysis crucial.

# About the U and Th decay series

- The energy and lifetime of  $\alpha$  decay vary depending on the nuclide.
- The sequence of decays leading to a stable final product is called a decay series.
- In nature, the main ones are the U series starting from  $^{238}\text{U}$  and the Th series starting from  $^{232}\text{Th}$ .



# Merits of nuclear emulsions

- Can obtain information on U and Th while covering a large area of several tens of centimeters with micrometer-level resolution.
- Can integrate data over time scales exceeding 100 days,  
→ a goal difficult to achieve with other detectors.
- A high-speed analysis method using an automatic scanner has been established,  
→ enabling easy and efficient measurements.

# Alpha decay in nuclear emulsions

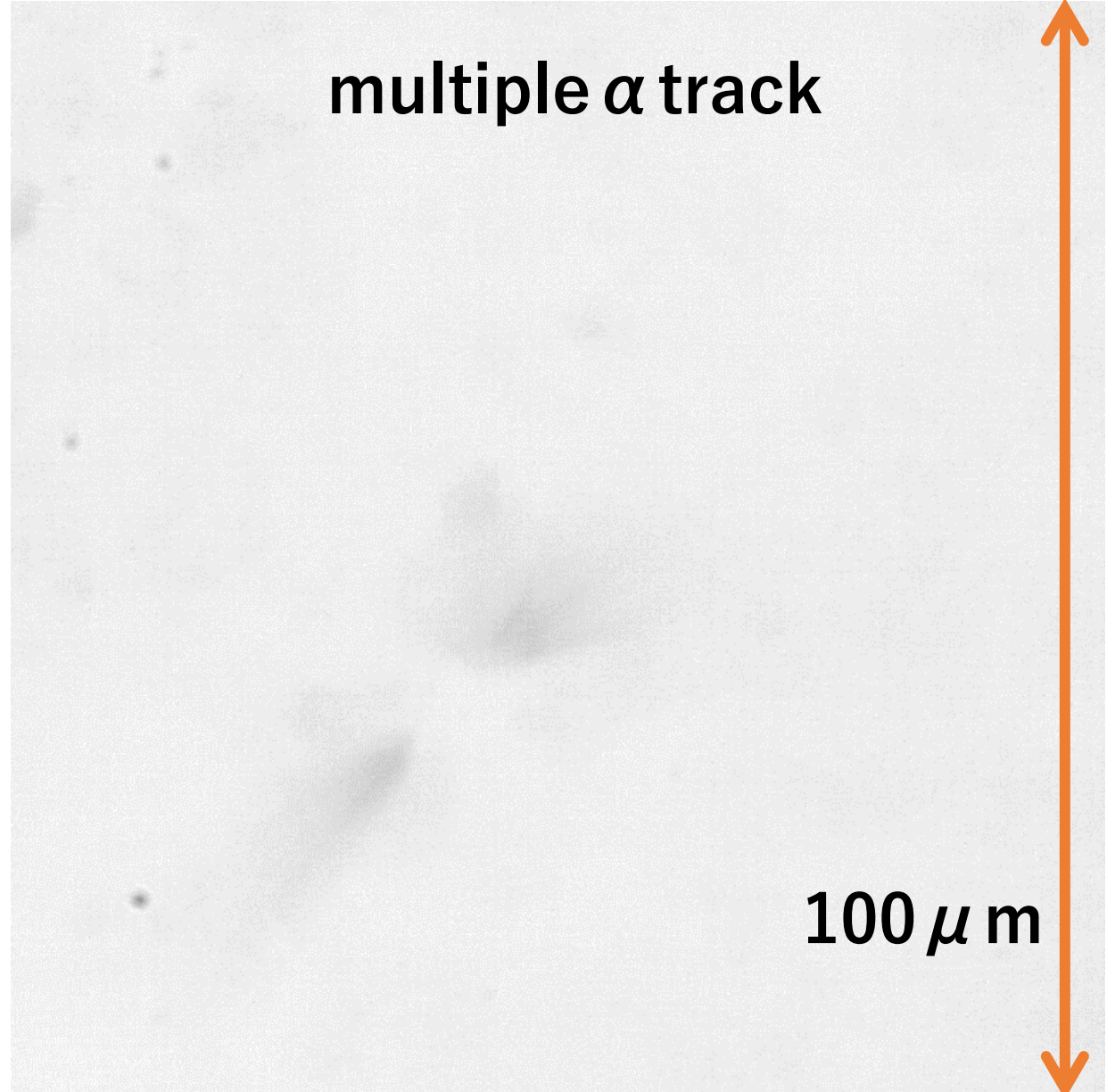
one  $\alpha$  track

100  $\mu$  m



multiple  $\alpha$  track

100  $\mu$  m



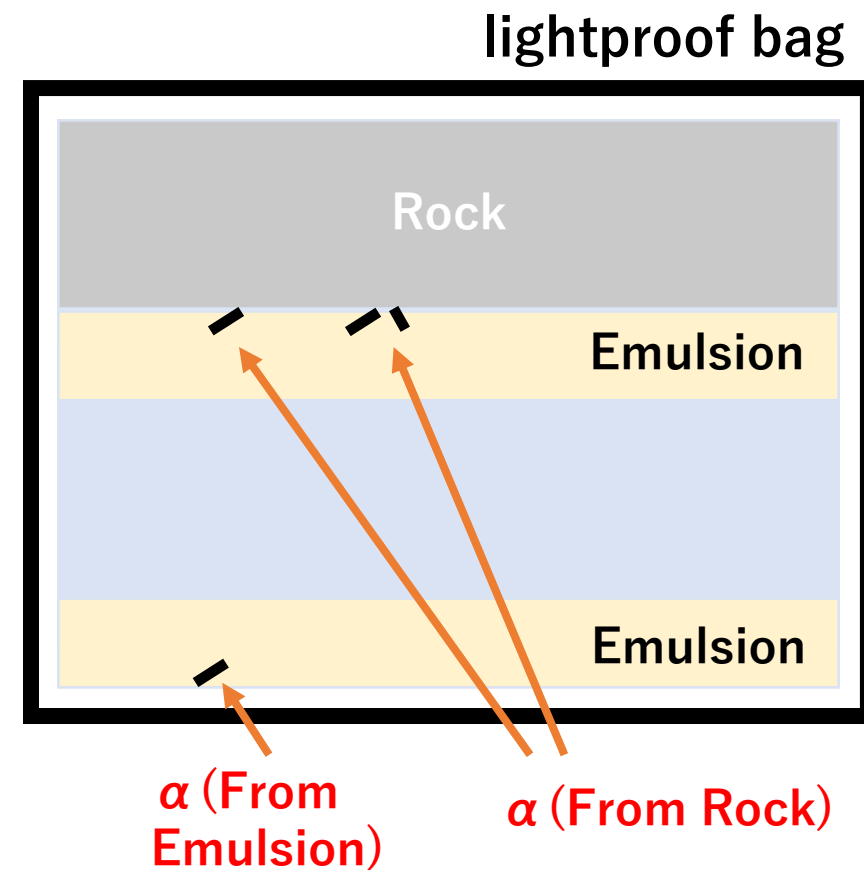
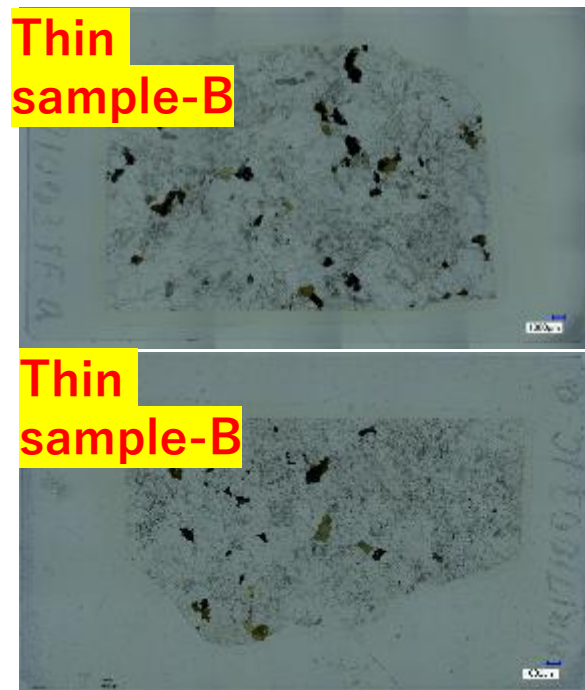
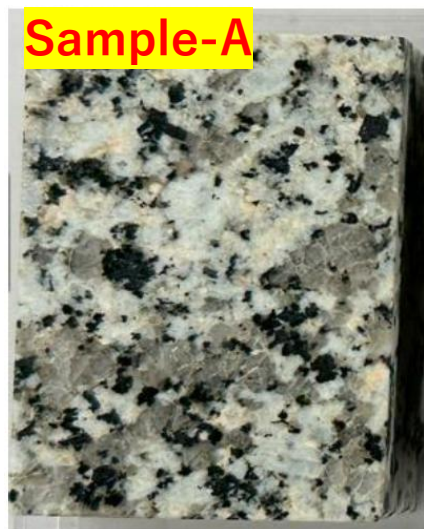
- **Goal: To constrain the systematic uncertainties in the  $\bar{\nu}_e$  flux model of the Earth's crust.**  
(based on the hypothesis that U and Th are more concentrated at grain boundaries than within minerals).
- Using nuclear emulsions to observe  $\alpha$  particles emitted from rocks. Preparing a high-speed analysis system for the recorded  $\alpha$  tracks.
- Analyzing the recorded  $\alpha$  tracks to determine their spatial distribution and emission angles.  
→ From these, the emission points of  $\alpha$  particles and thus the distribution of U and Th in rocks—can be revealed over a much larger area than conventional methods.

# Experiment: Rocks

10

The nuclear emulsion and rock sample were vacuum-sealed in a lightproof bag and stored for about 100 days.

## Rock samples

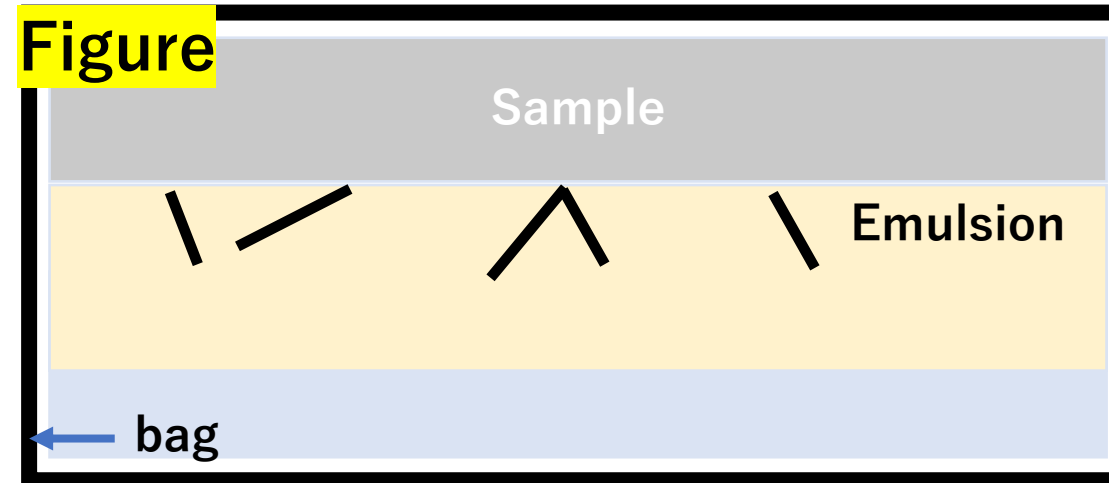


- Since tens of thousands of  $\alpha$  tracks were observed under the microscope, machine learning was used for rapid processing.

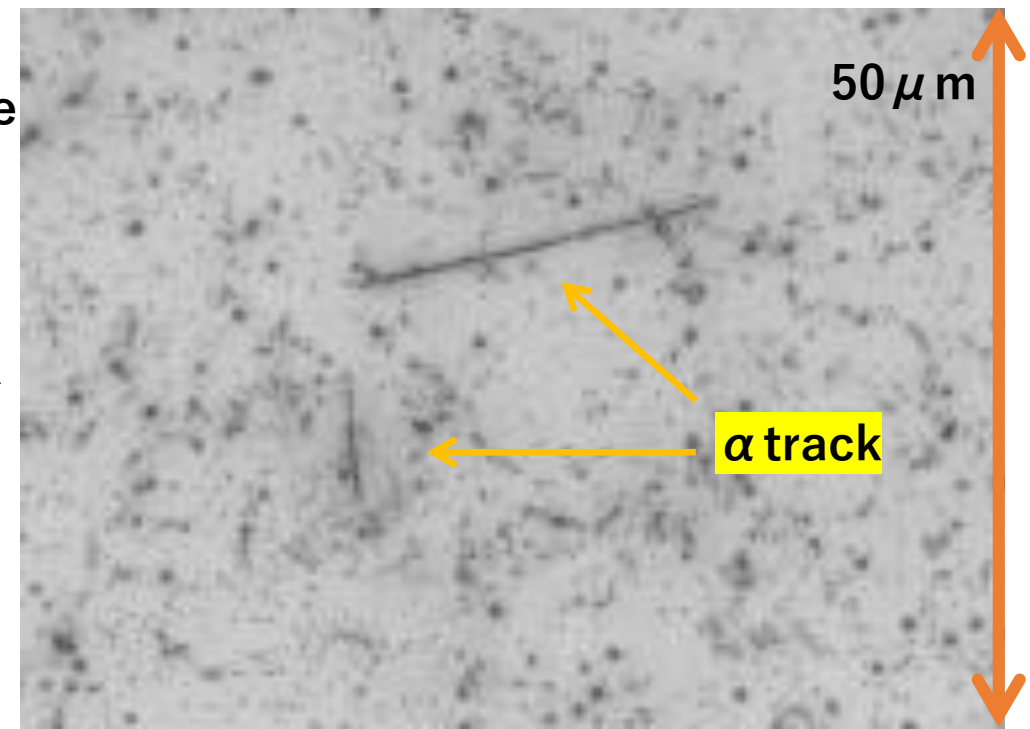
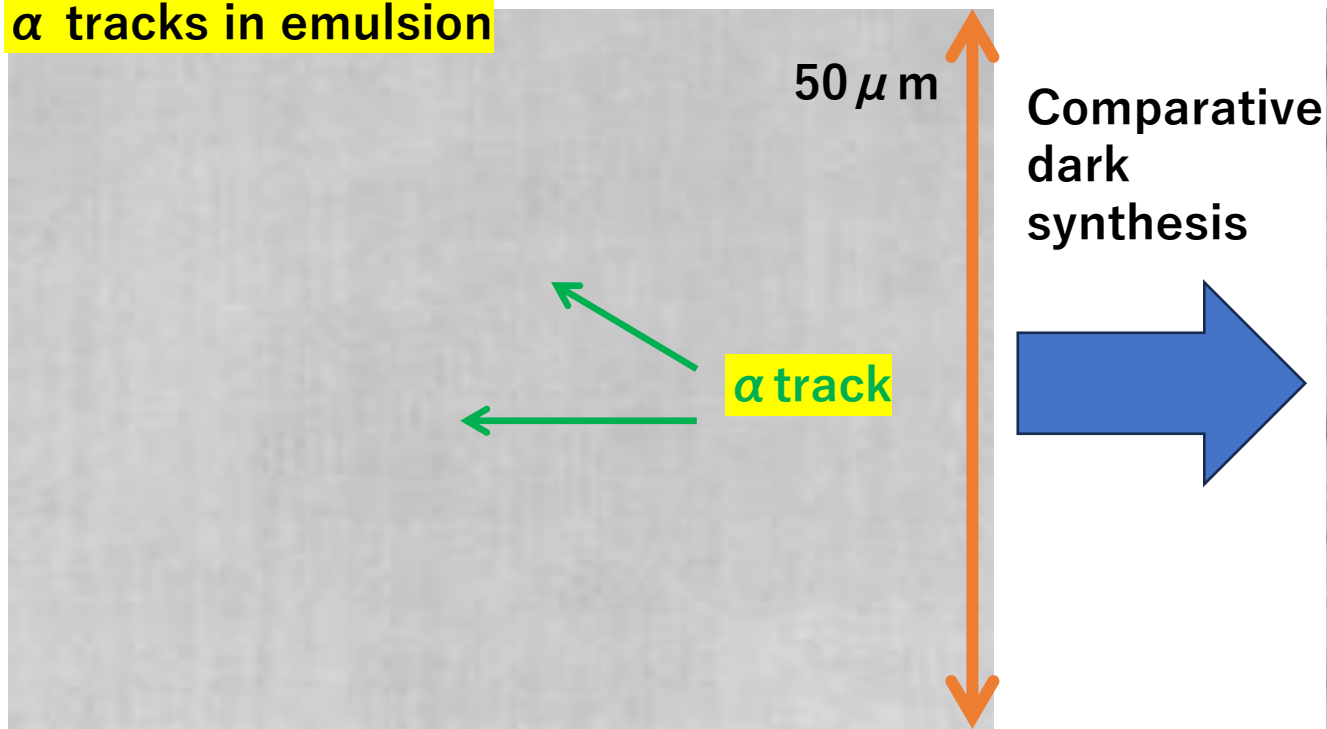
# Measurement using machine learning 11

- The sample and emulsion were vacuum-sealed in close contact, and 64 layers were imaged in the depth direction at  $1\ \mu\text{m}$  intervals using HTS2, then combined into a single image through comparative dark synthesis.

Figure

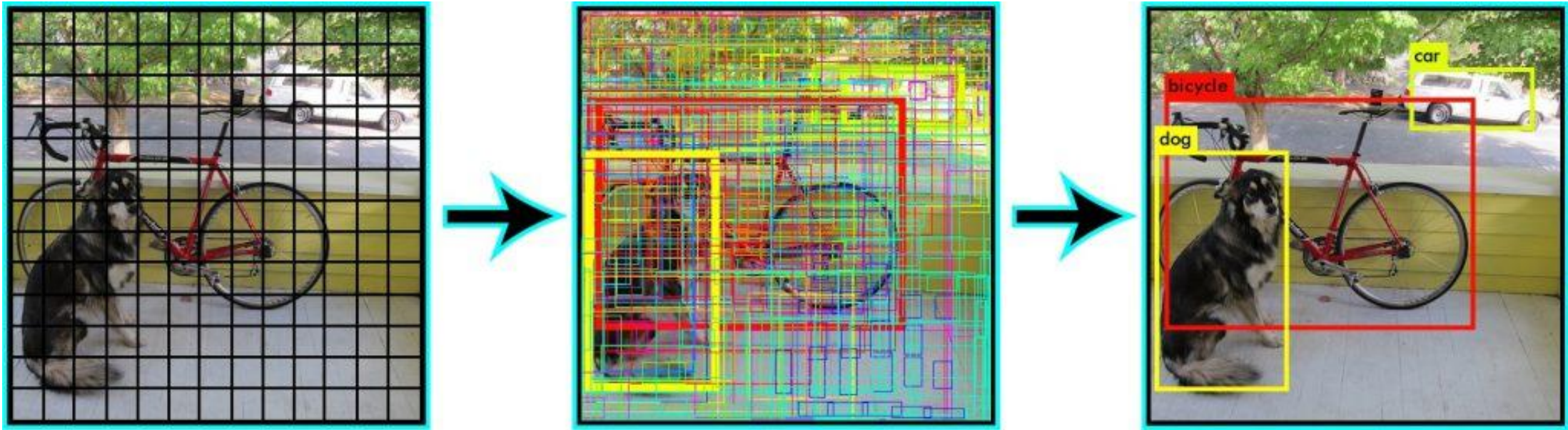


$\alpha$  tracks in emulsion



# Measurement using machine learning <sup>12</sup>

- About the machine learning model (YOLO series)
  - The input image is divided into grids of various sizes.

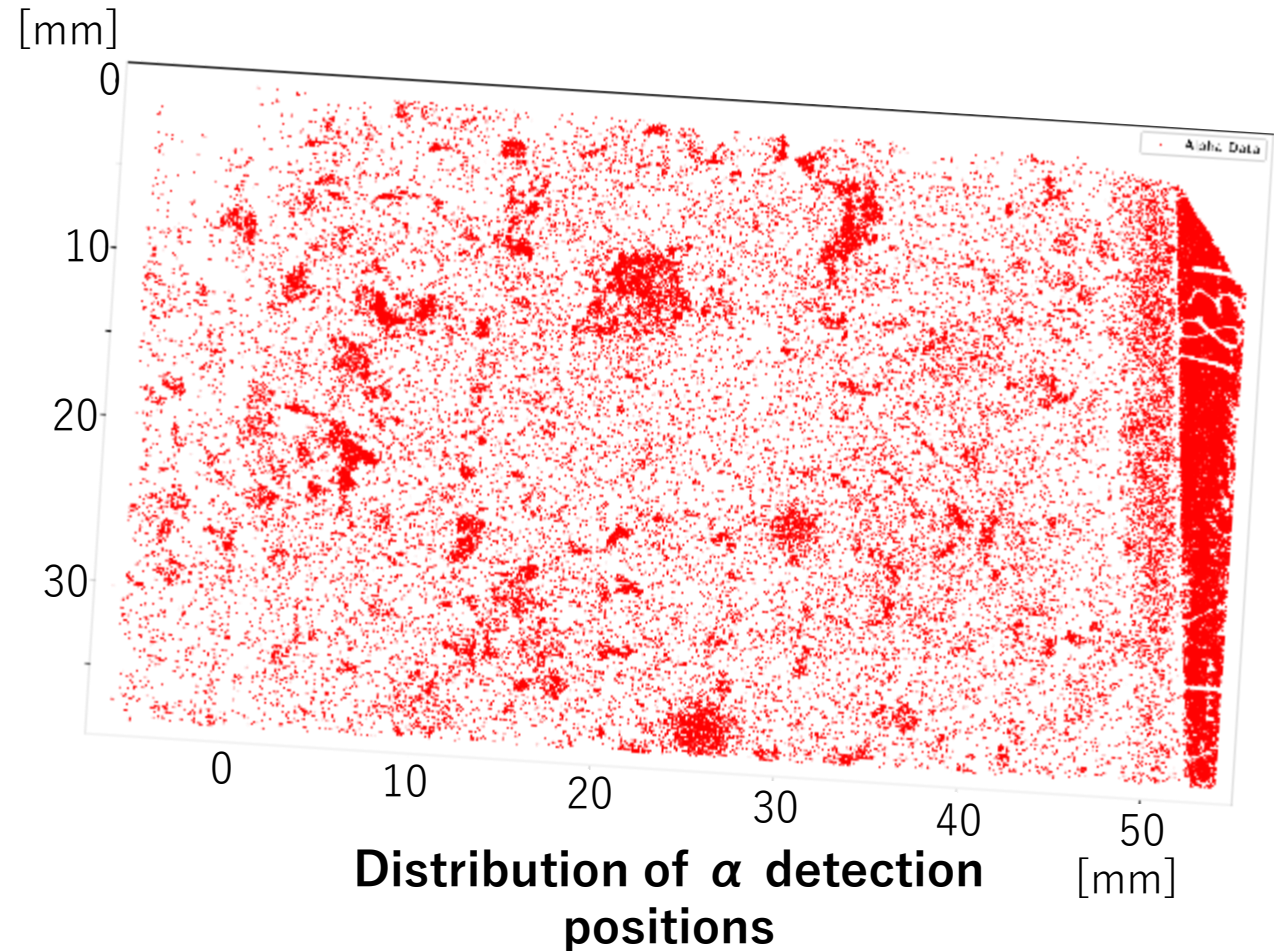


- For each grid cell, the model compares with the trained data to estimate the probability of an object's presence, and regions with probabilities above a certain threshold are recognized as detections.
- The comparative dark-synthesized images were used as training data.

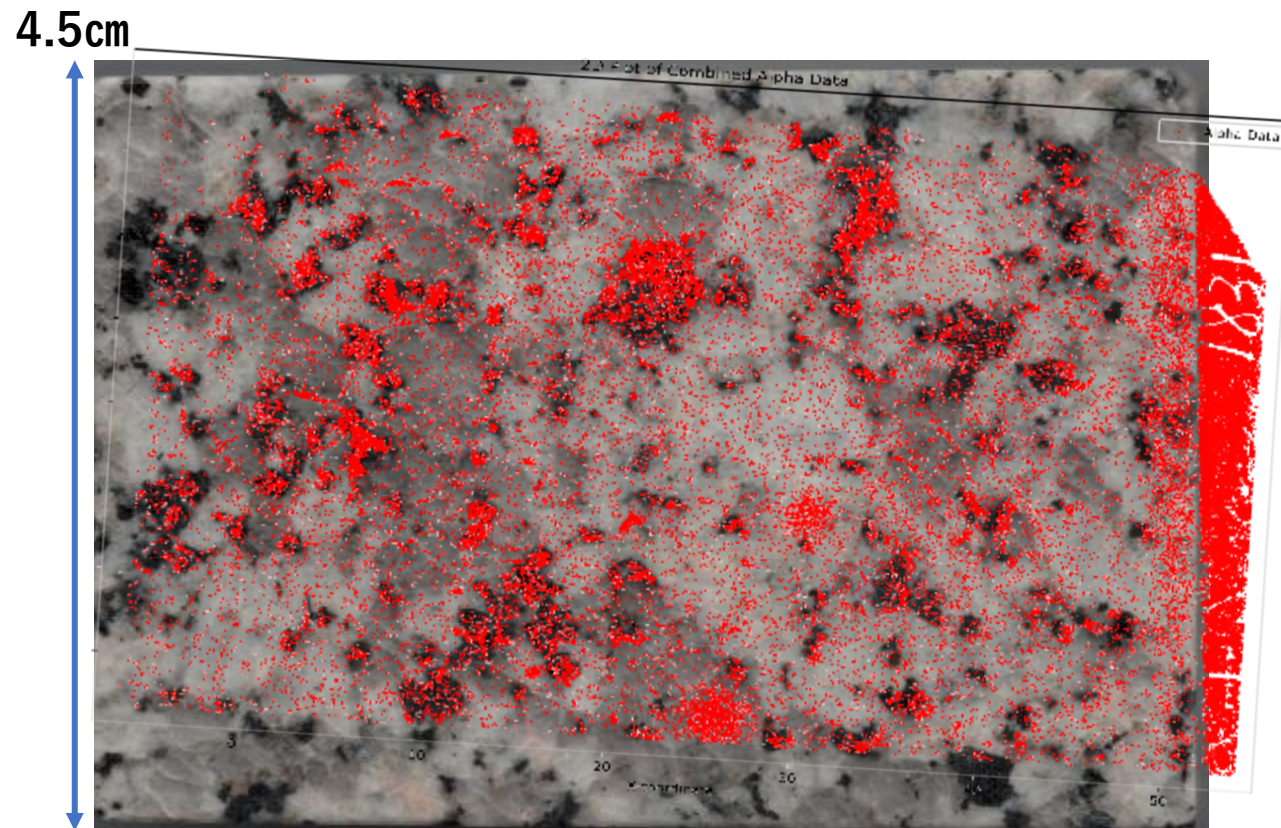
- Alpha particle detection results for Rock A and the emulsion

4.5cm

Sample-A



## • 岩石との位置合わせ結果



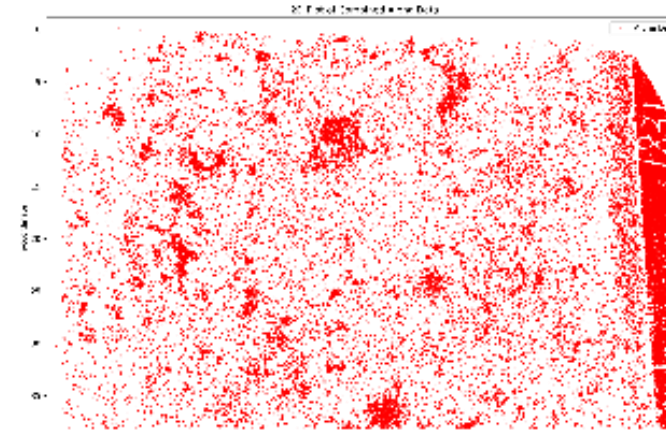
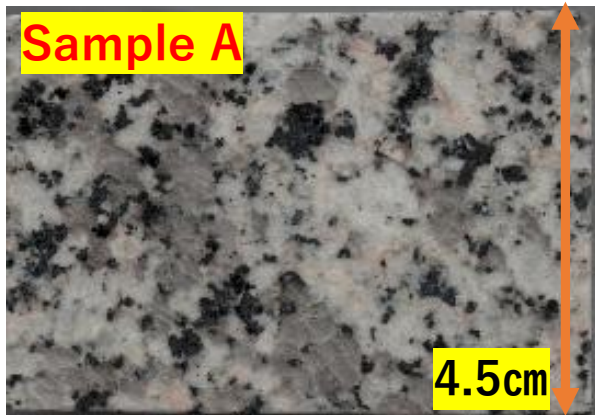
- The  $\alpha$ -particle distribution was biased according to the rock's mineral distribution.

→  $\alpha$  tracks were more densely clustered in the dark regions (biotite) than in the white/gray regions (quartz, feldspar).

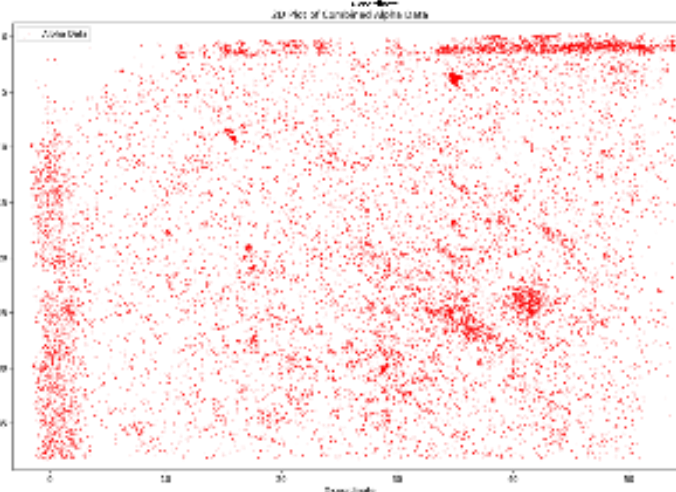
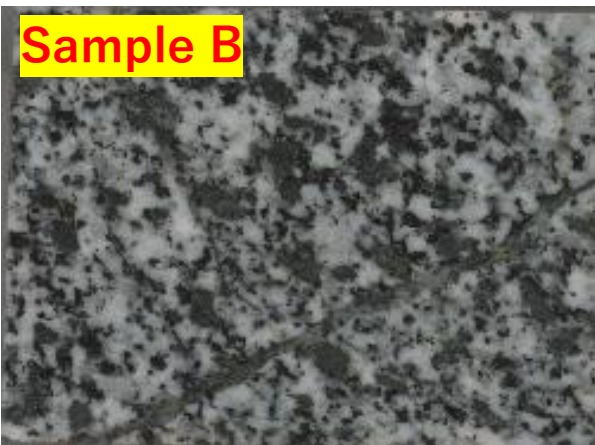
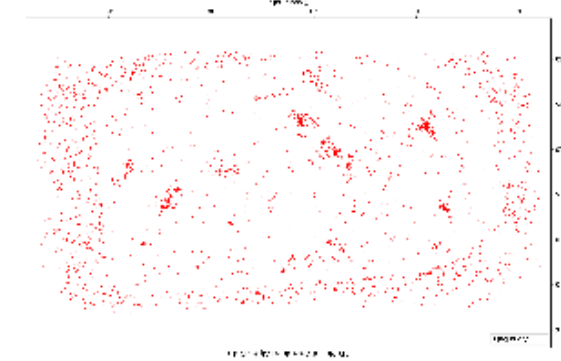
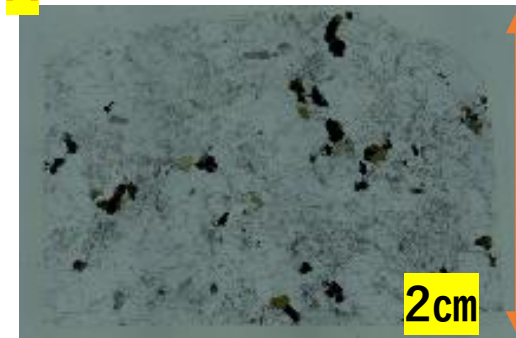
→ This supports the interpretation that biotite contains higher U and Th.

→ The edge-localized clusters of  $\alpha$  tracks seem to have formed due to migration of **Rn-222 (half-life: 3.8 days)**.

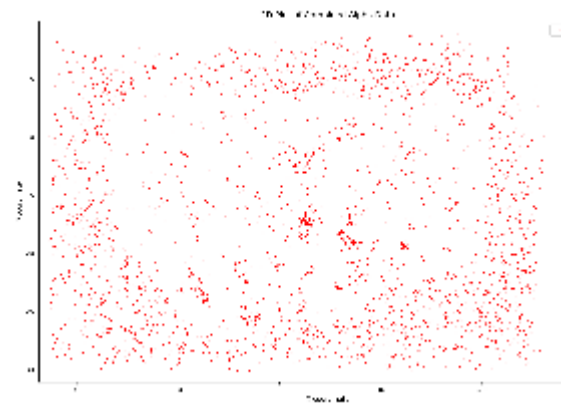
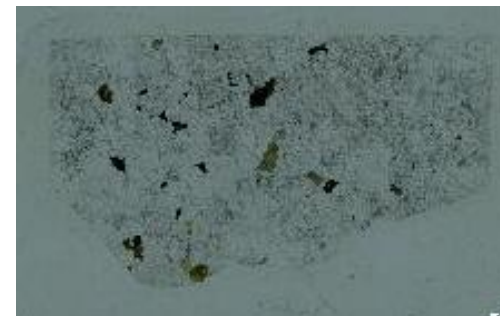
- Alpha particle detection results for the rock and the emulsion



**Thin Sample-A**



**Thin Sample-B**



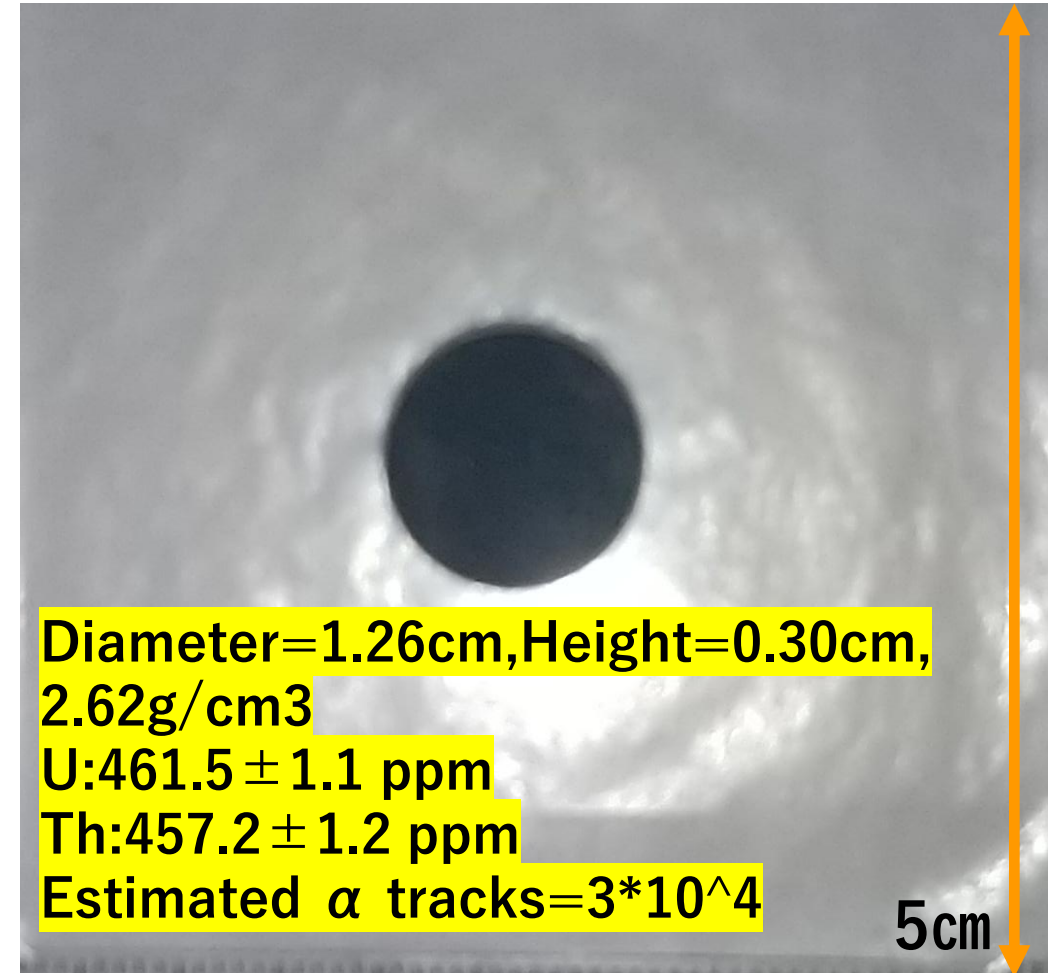
# Toward quantitative analysis

1. Evaluation of **S/N** ratio
2. **Track length** measurement in the emulsion
3. Estimation of decay points and nuclides from **VTX** formation

# Detection efficiency and S/N evaluation<sup>17</sup>

- 20-day measurement was conducted using the NIST SRM 610 reference material, which has a uniform concentration of U and Th.
- All 4,032 fields of view were manually labeled using Labellmg, and 30,136  $\alpha$  tracks were compared with the YOLO detection results.

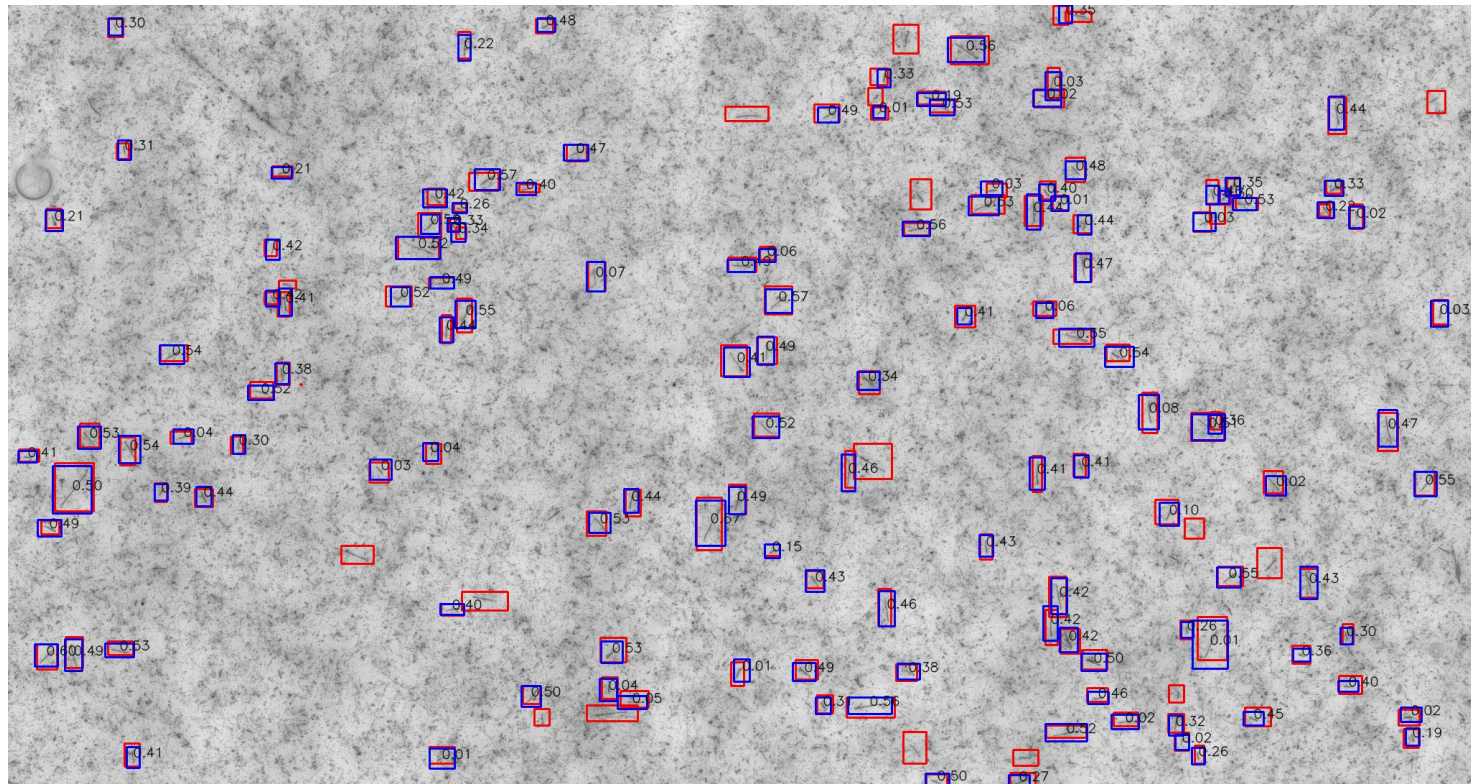
NIST SRM 610試料



# Detection efficiency and S/N evaluation<sup>18</sup>

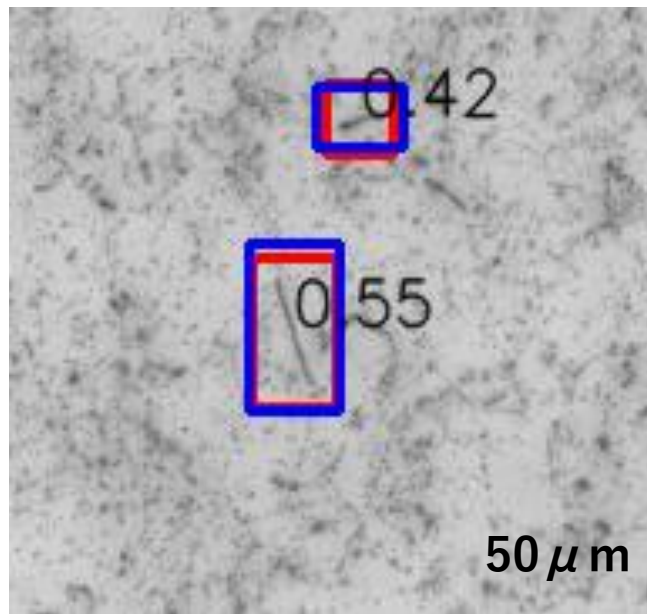
- A successful detection was defined as a case where the center of the YOLO bounding box was within 5 pixels of the true position, and the side-length ratio differed by no more than 25%.

matching image.

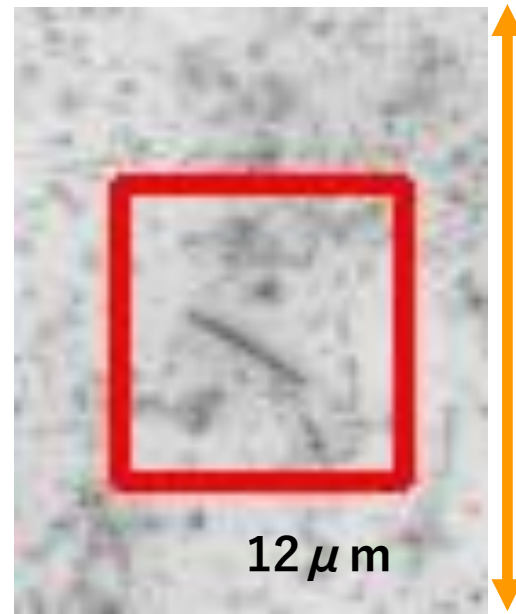


# Detection efficiency and S/N evaluation<sup>19</sup>

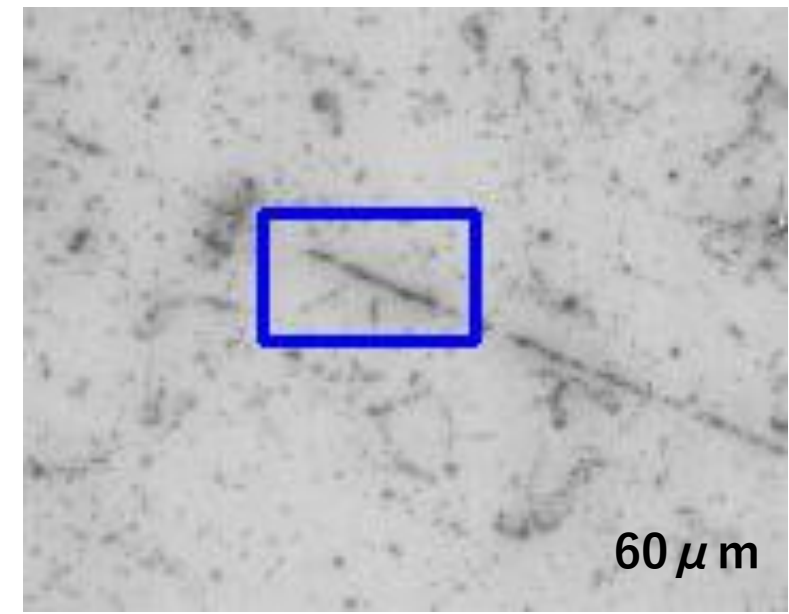
- **Red rectangle = Human**    **Blue rectangle = Yolo**
- When multiple candidates were present, the one whose bounding box center was closest to the manually labeled position was used for comparison.



matched

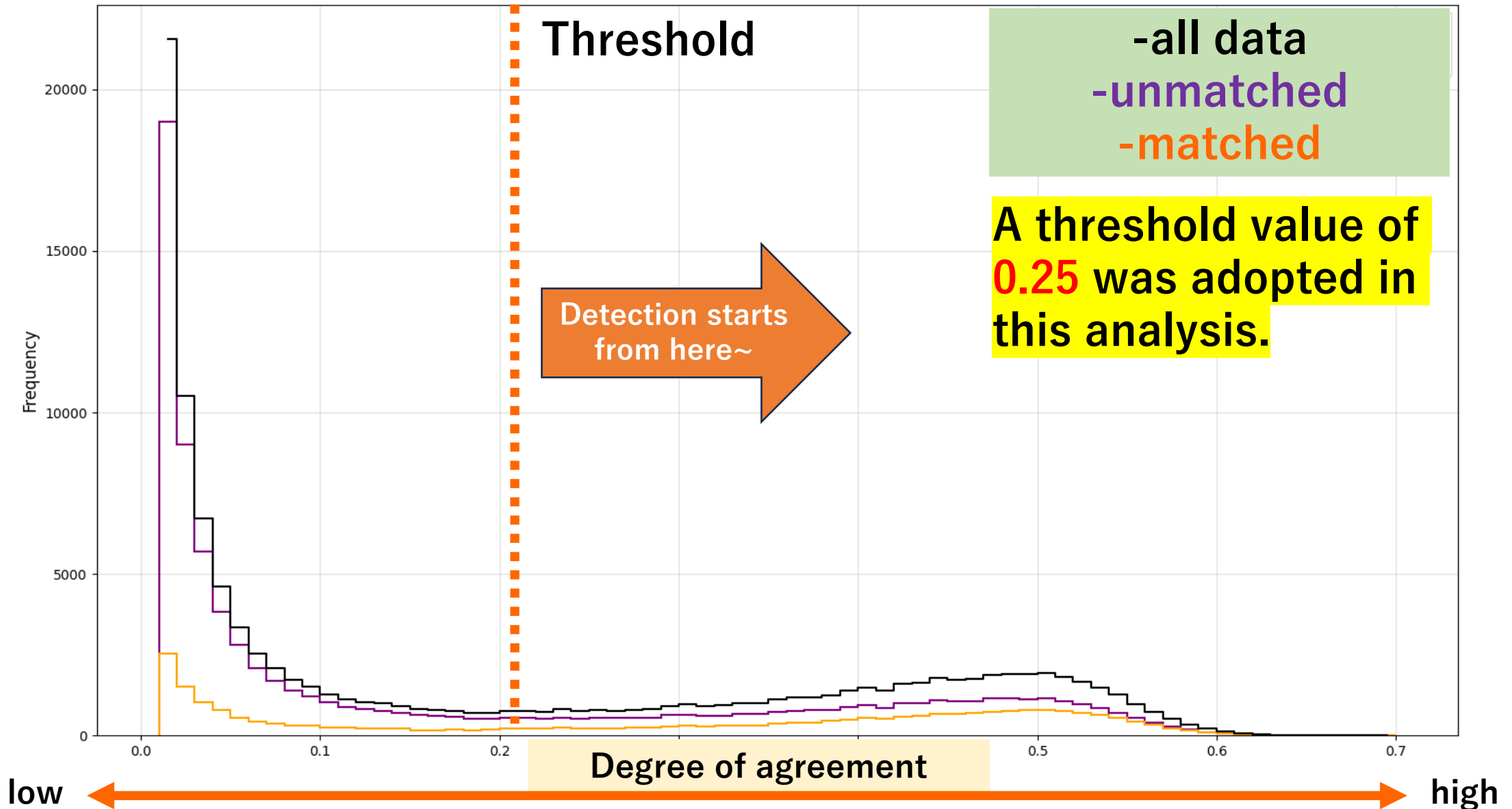


Not matched  
(Human only)

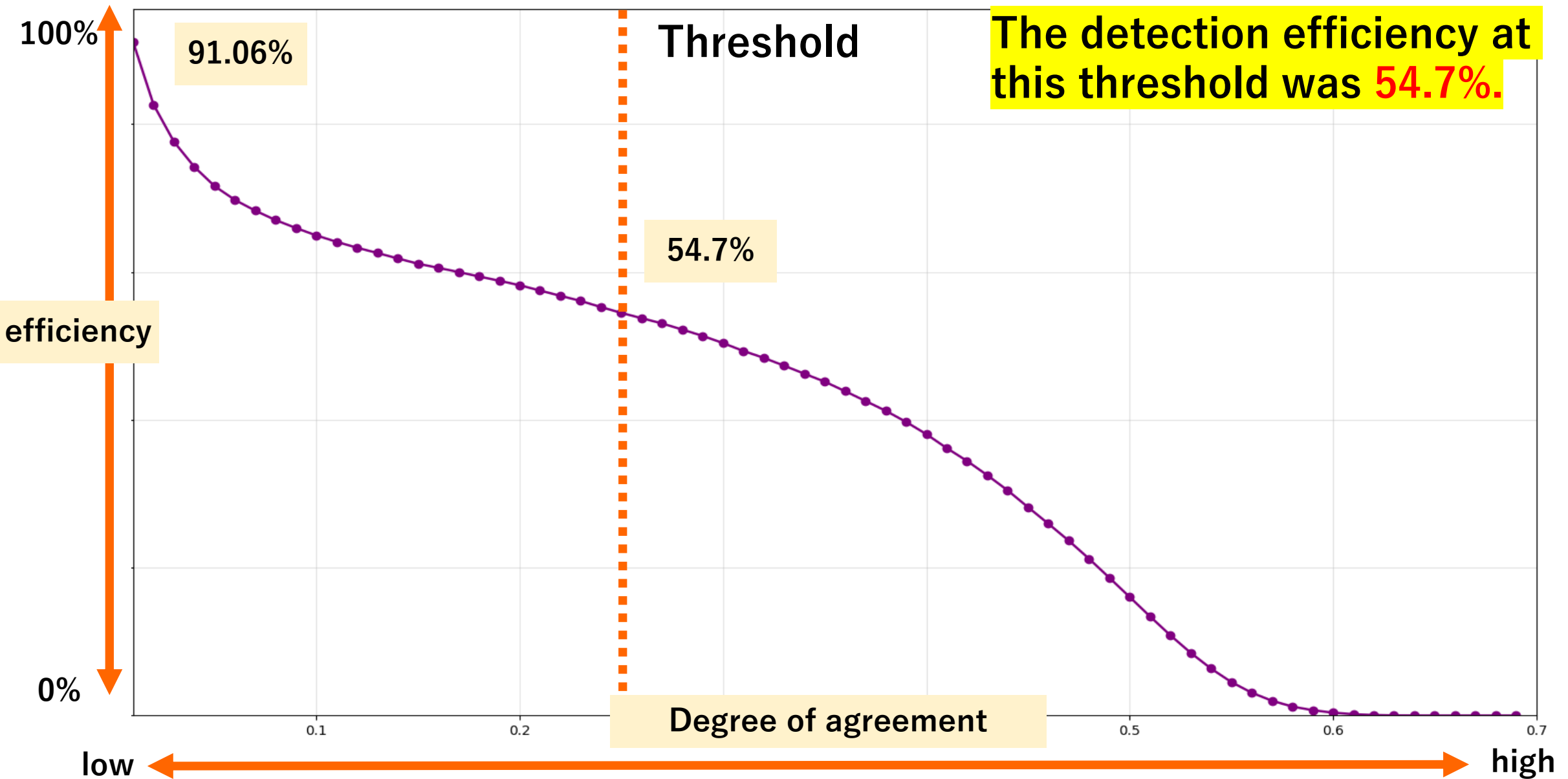


Not matched(False)

# Detection efficiency and S/N evaluation<sup>20</sup>



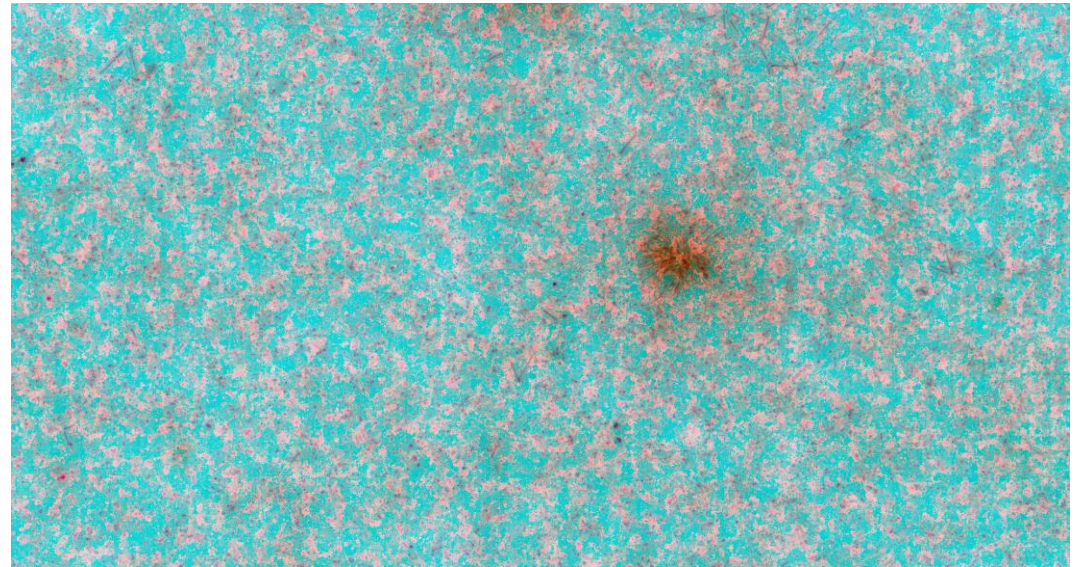
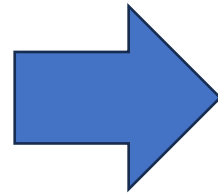
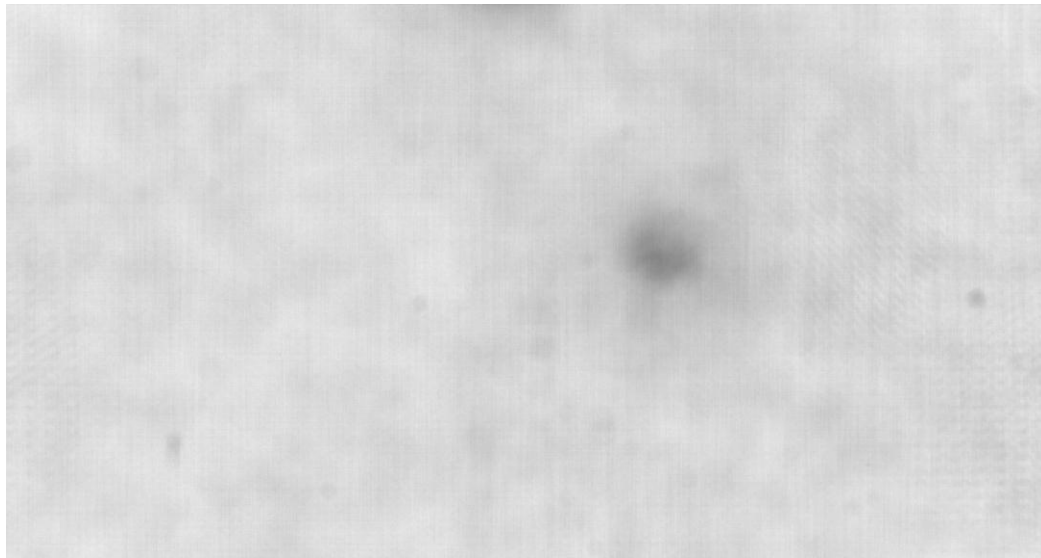
# Detection efficiency and S/N evaluation<sup>21</sup>





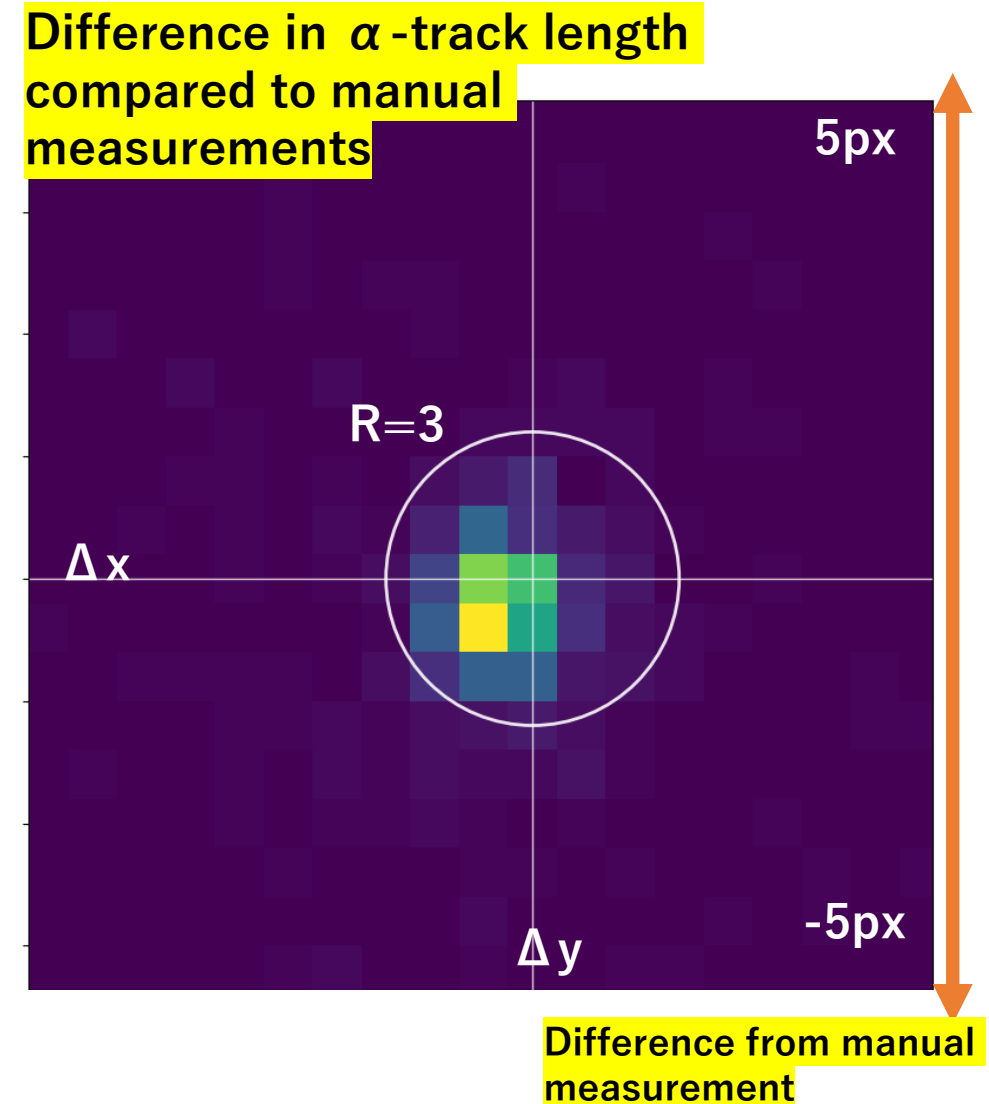
# Measurement of $\alpha$ -particle track length<sup>23</sup>

- To measure the length of  $\alpha$  tracks in three dimensions, a color image for length analysis was created by adding information on the **depth with the darkest image**, the **minimum brightness**, and the **average brightness** to the comparative dark-synthesized image.
- We developed an automatic length-measurement script and compared its results with the manually recorded lengths.



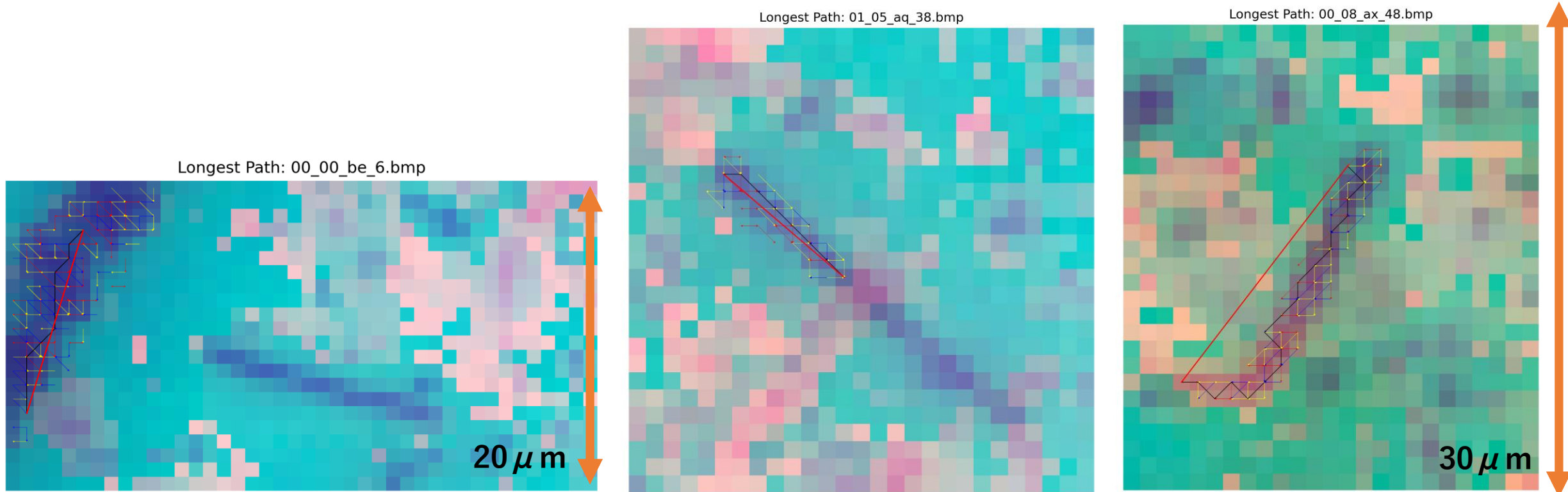
# Measurement of $\alpha$ -particle track length<sup>24</sup>

- Measurements within an error of  $2\ \mu\text{m}$  ( $=3\ \text{px}$ ) relative to manual values were regarded as successful.
- Of the 648  $\alpha$  tracks in the SRM, 542 were judged successful.  
→ **83.6% success.**
- We inspected images of  $\alpha$  tracks with large errors to identify the causes.



# Measurement of $\alpha$ -particle track length<sup>25</sup>

- The main causes of failure were fitting errors, mask detection errors, and incomplete track length measurements.  
→ These issues will be addressed in future analyses.

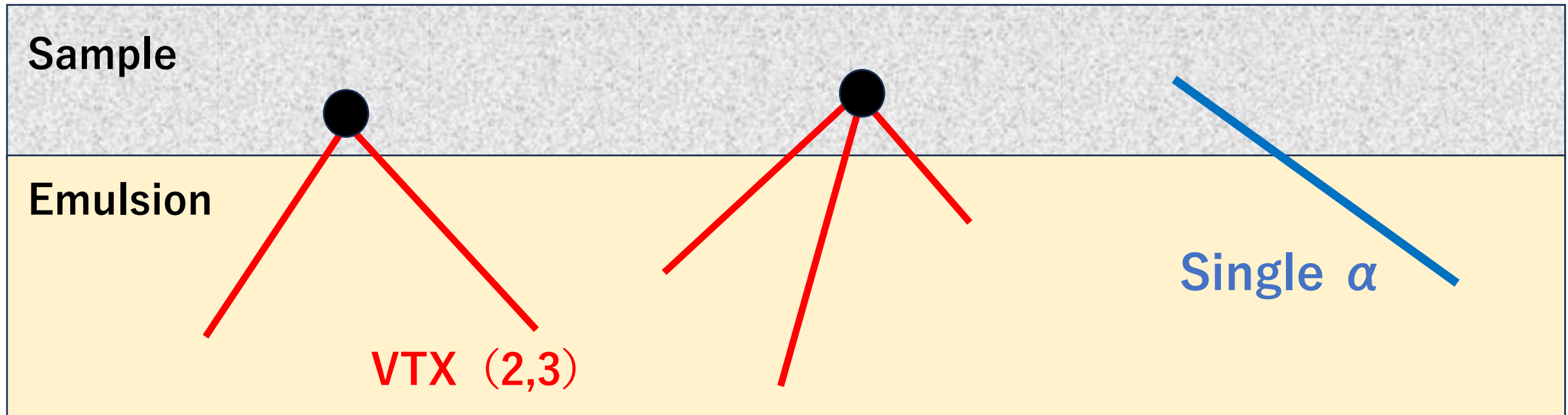


- From the incident points recorded in the length measurements, each  $\alpha$  track was extended toward the rock side, and intersections between tracks were searched for.
- Since short-lived nuclides undergo successive decays without significant movement, **their decay chains can form vertex (VTX) structures.**
- The distance from the intersection point to the end of each track corresponds to the  $\alpha$ -particle energy, **enabling identification of the emitting nuclide.**

# VTX (Vertex) measurement

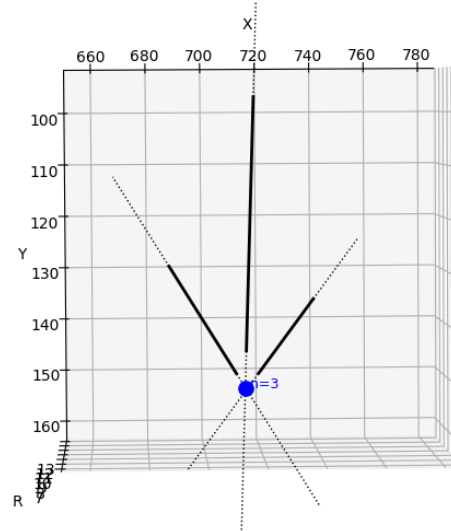
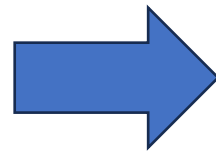
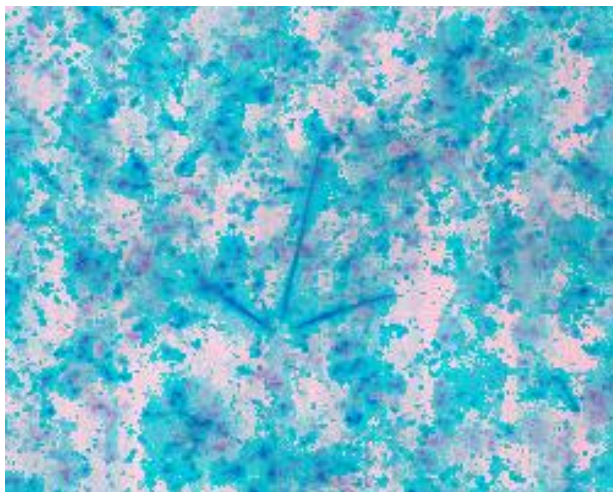
27

- From the incident points recorded in the length measurements, each track was extended toward the rock side.
- When two tracks approached within  $1\ \mu\text{m}$  of each other, the point was defined as a VTX (vertex).
- If multiple VTX points were found within  $1\ \mu\text{m}$  of each other, they were merged into a single vertex.



# VTX (Vertex) measurement

- This analysis was applied to 20 visually confirmed VTX events, and all were successfully identified as VTX structures.
- When applied to 10 images of NIST SRM 610, which contains only U and Th, no VTX structures were detected.
- Further analyses will be conducted over larger areas in the future.



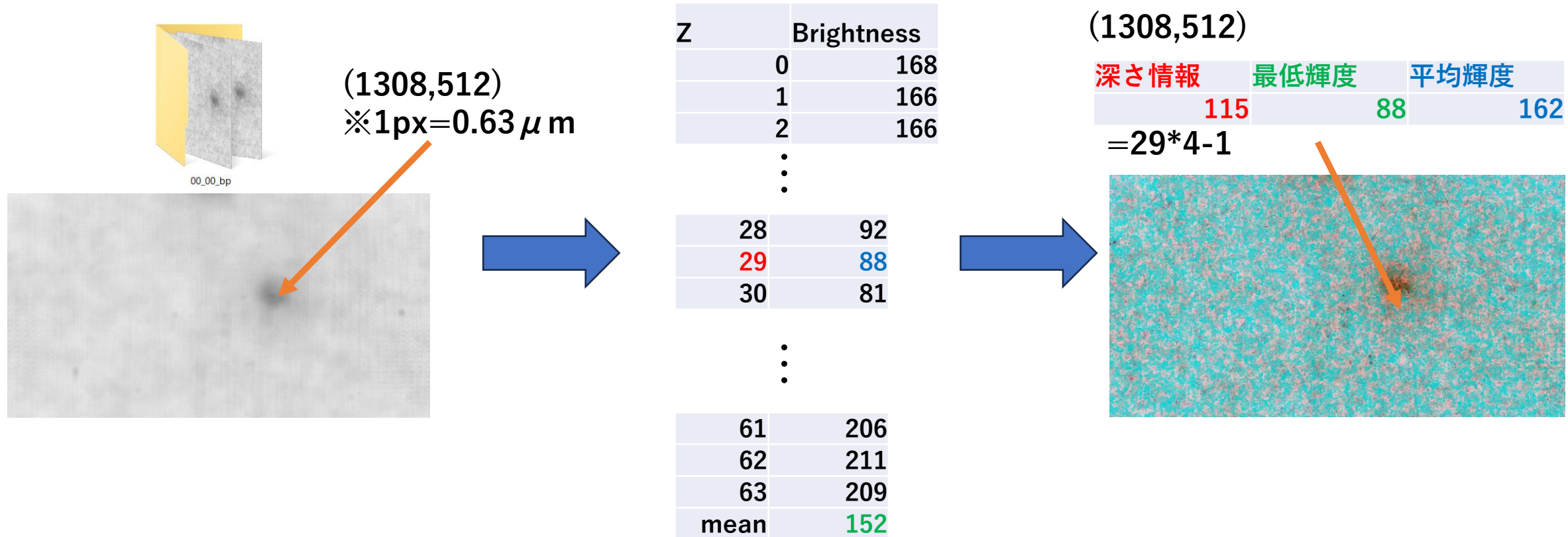
- **The length and VTX measurement processes will be evaluated more quantitatively.**
- **To more accurately assess detection efficiency, simulations using tools such as Geant4 will be performed.**
  - **Verify whether there are biases in the training data depending on track angle or length.**
  - **Ultimately, determine detection efficiency as a function of angle and length.**
- **In the future, long-term and systematic automatic measurements will be carried out for various rock samples.**
- **The developed methodology will be applied to research in both geoscience and particle physics.**

- We successfully developed **a high-speed  $\alpha$ -track detection method using machine learning and nuclear emulsions.**
  - This provides a new measurement technique to investigate the distribution of radioactive nuclides containing U and Th in rocks.
- The detection efficiency was quantitatively compared with manually-labeled data.
- By measuring  $\alpha$ -track lengths, we will also study the energy and angular distributions of the incident  $\alpha$  particles.
  - Future measurements will be conducted on various rock samples.
- These results will contribute to refining the current neutrino flux models.

Thank you for listening!

# Appendix

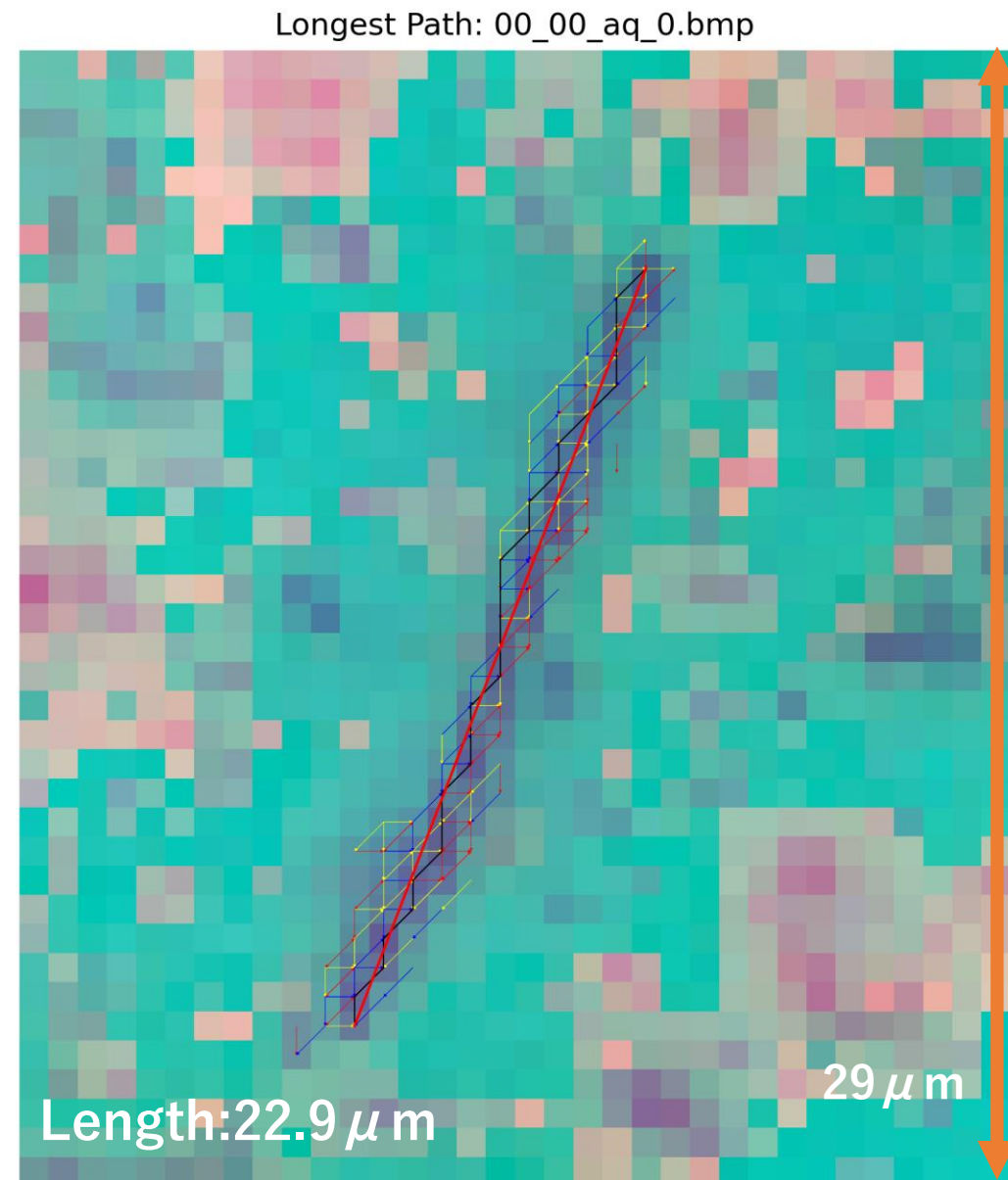
# length measurement



# length measurement

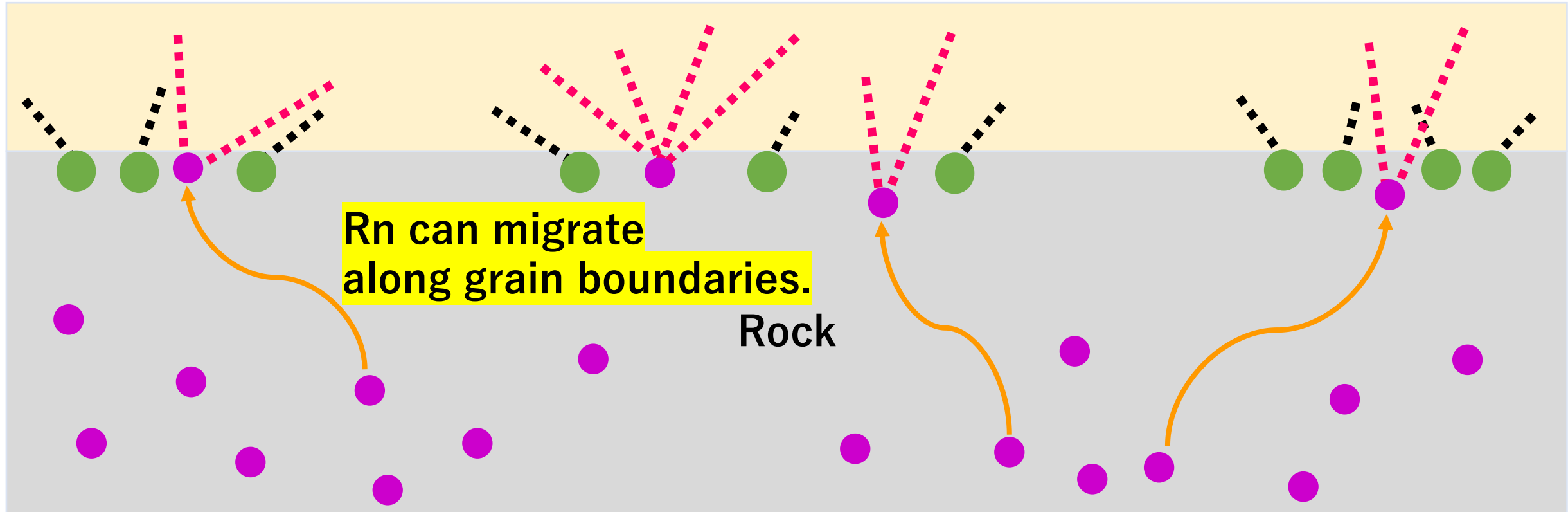
34

- For length measurement images, masks were created using the minimum and average brightness channels, and adjacent pixels were connected
- when the depth difference was **0** →, **4** →, or **8** →.



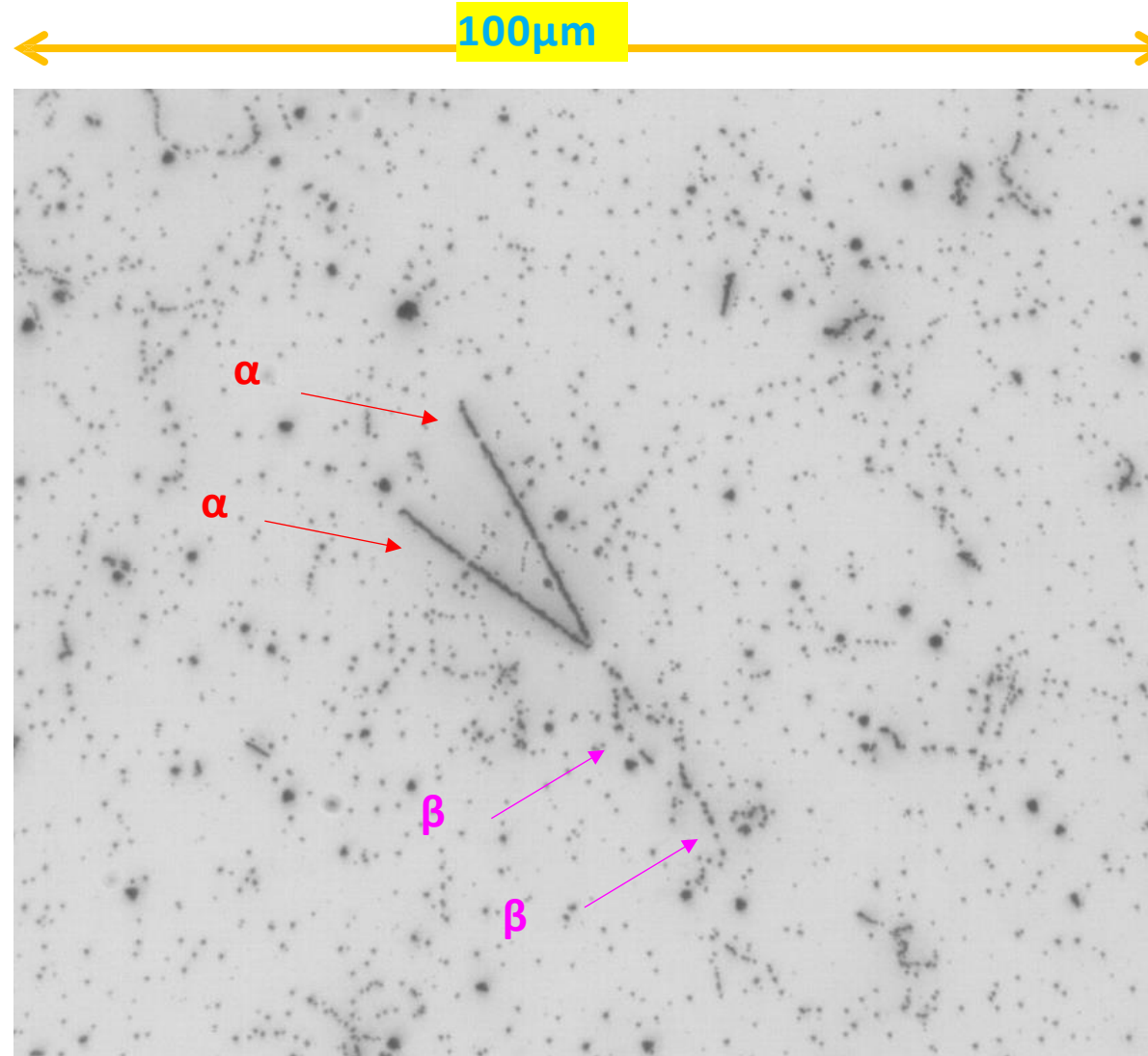
# Rn in Rocks

- Rn in rocks lead to an overestimation of decay counts of U and Th.

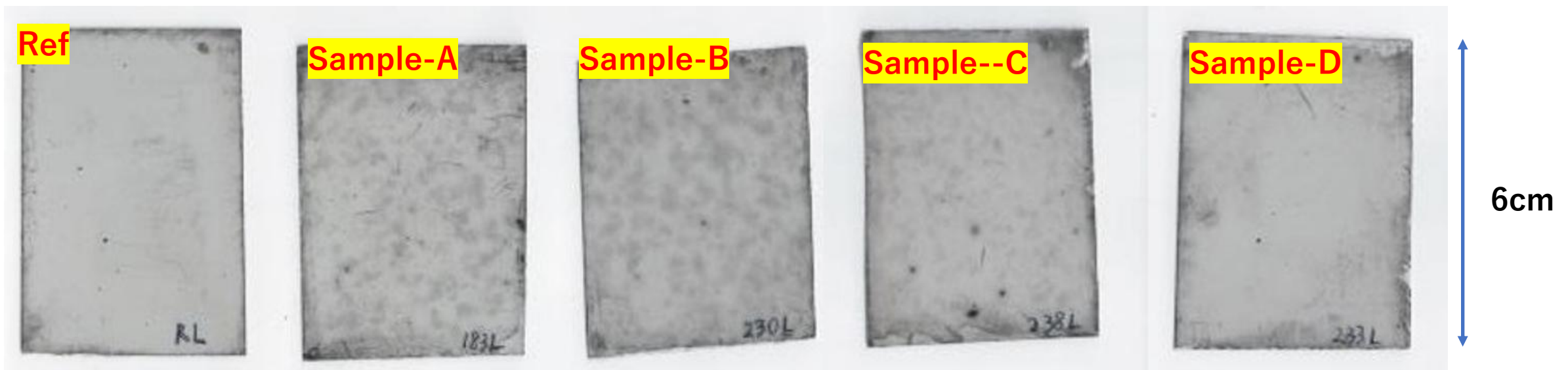


- Rn goes a series of  $\alpha$  decays in a short time, **leaving up to 4  $\alpha$  tracks in the emulsion** → We will use this feature to distinguish (separate) them!

# Beta decays in Rock



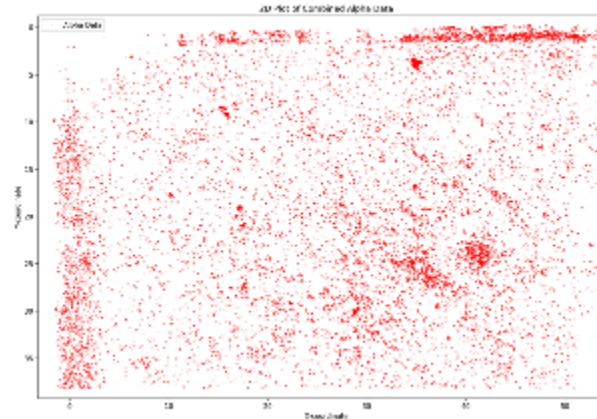
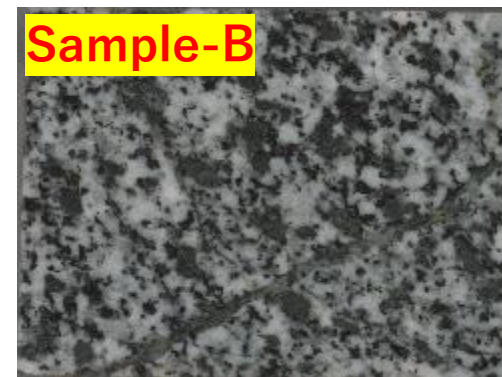
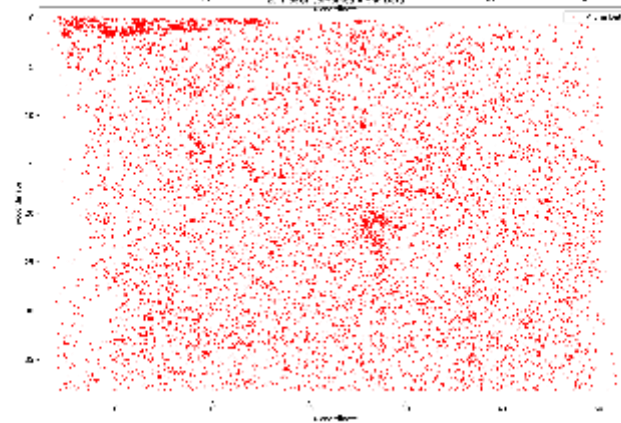
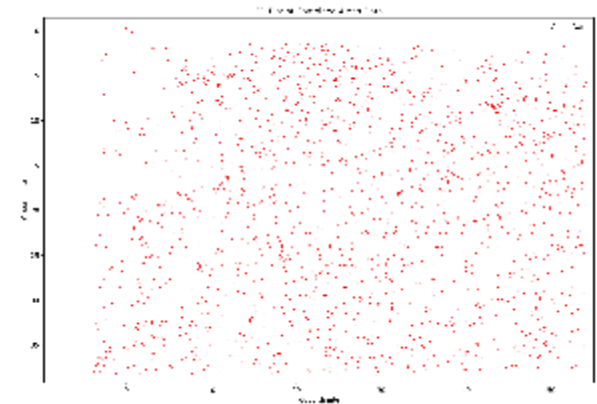
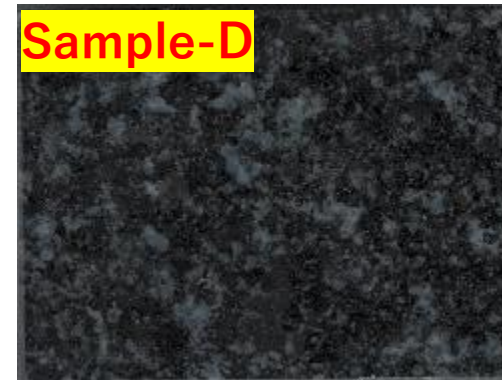
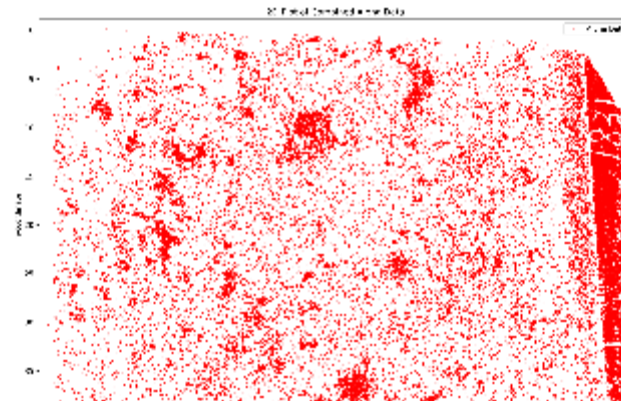
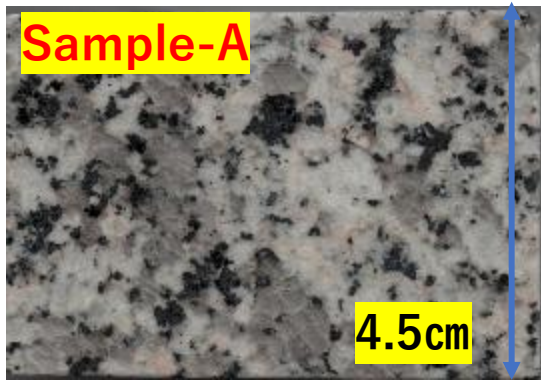
# Shading appearing in the emulsion (Beta)<sup>37</sup>



- After the experiment, **shading remained on the emulsion**, and visual inspection confirmed that **these patterns corresponded to the mineral distribution of feldspar**.
- These variations were not observed in the reference or the Sample-D
- Sample D was prepared using **gabbro**.

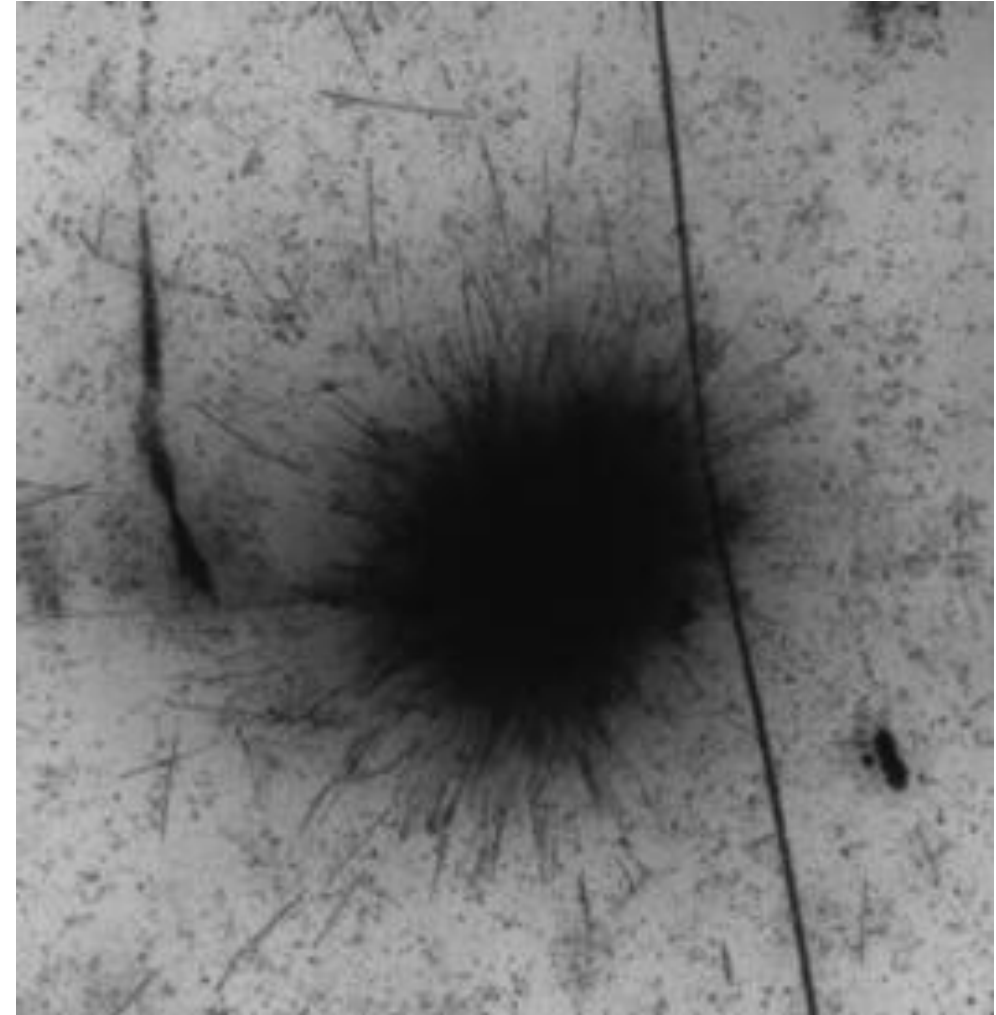
# Other Rock Samples

- Result A~D

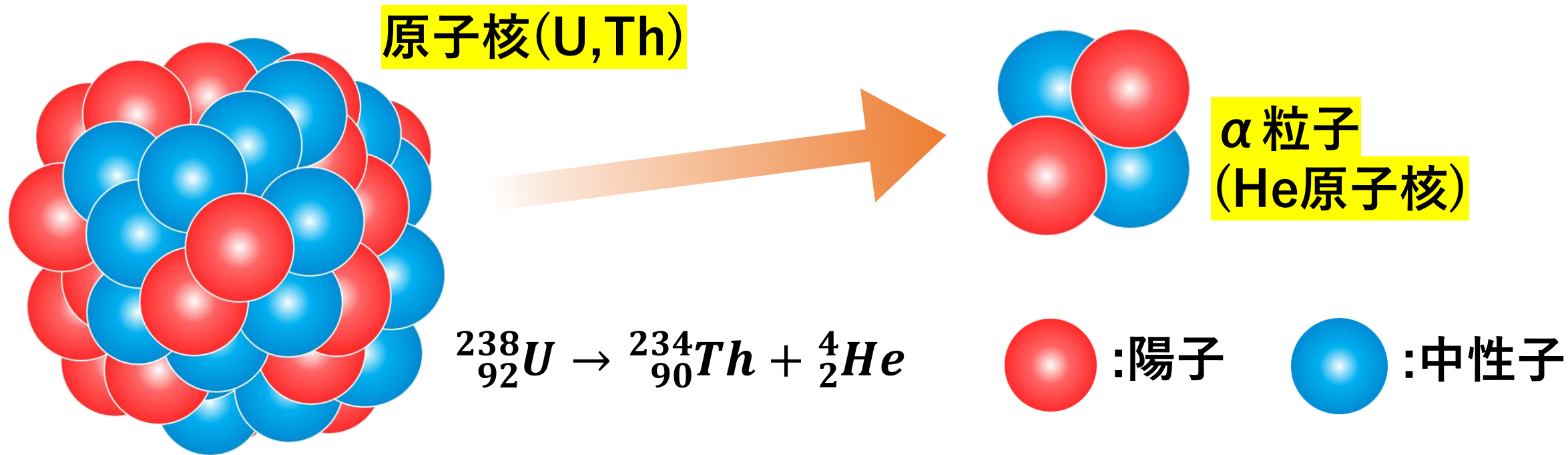


- Some regions showed dense clusters of  $\alpha$  tracks.  
→ Possibly minerals with high U and Th concentrations?  
(e.g., monazite, zircon)
- Several tens of such clusters were found per emulsion plate.

50  $\mu$ m



# $\alpha$ 崩壊について



- ${}^{238}\text{U}$ ,  ${}^{232}\text{Th}$ のような重い放射性核種は経時的に高エネルギーの $\alpha$ 粒子を放出し、より軽い原子核になる( $\alpha$ 崩壊)
- これらは原子核乾板で20~40  $\mu\text{m}$ の太く短い飛跡として観察できる